EVALUATION OF RESERVOIR OPERATION ALTERATIONS TO IMPROVE WATER SUPPLY, HYDROPOWER GENERATION, AND FLOOD CONTROL PERFORMANCE OF TARBELA DAM

by

Ahmed Rafique

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STATEMENT OF THESIS APPROVAL

The thesis of **Ahmed Rafique**

has been approved by the following supervisory committee members:

Steven J. Burian	, Chair	**03/21/2018** Date Approved
Michael E. Barber	, Member	**03/21/2018** Date Approved
Erfan Goharian	, Member	**03/22/2018** Date Approved

and by **Michael E. Barber** , Chair/Dean of

the Department/College/School of **Civil and Environmental Engineering**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

Tarbela Dam is the largest in Pakistan, providing significant fractions of the country's irrigation supply, hydropower generation, and flood control. The operation of Tarbela Dam has been based on maximizing the release of water for irrigation supply. This single objective approach has provided benefits for Pakistan but has not maximized the potential of Tarbela Dam for targeting multiple objectives and considering multiple criteria. In this study, a model was created with the Water Evaluation and Planning (WEAP) System and used to explore the impact of altering the operations of Tarbela Dam in terms of reliability, resilience, and vulnerability (RRV) for the three objectives of irrigation supply, hydropower generation, and flood control. The reservoir performance for the altered operations was compared to the performance following historical operations for both historical and projected future climate and water demand conditions. Simulation results show that a new proposed operations strategy tested under historical climate and water demand conditions would increase RRV by 17%, 67%, and 7%, respectively, for the water supply objective and 34%, 346%, and 22%, respectively, for hydropower generation compared to the historical reservoir performance. The flood control reliability would increase by only 0.3%. For projected future conditions, the proposed operations strategy would increase RRV by 7%, 219%, and 11%, respectively, for water supply and 19%, 136%, and 13% for hydropower generation. For flood control, the reliability would increase by only 2%, while resilience and vulnerability would decrease by 33% and 39%,

respectively. The study confirms the potential to improve the ability to provide more reliable and resilient irrigation supply and hydropower generation, although not to reduce vulnerability. The inability to improve flood control performance by altering operations confirms previous studies documenting the need for increased storage capacity. The use of multiple objectives and the RRV criteria is recommended as an approach to guide Tarbela Dam operations.

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LIST OF ABBREVIATIONS

AF	Acre Feet
AMSL	Above Mean Sea Level
BCM	Billion Cubic Meter
CFS	Cubic Feet per Second
IRSA	Indus River System Authority
IWT	Indus Waters Treaty
MAF	Million Acre Feet
MCM	Million Cubic Meter
MW	Megawatt
NSD	No Significant Difference
RRV	Reliability Resilience and Vulnerability
SD	Significant Difference
SE	Standard Error
St Dev	Standard Deviation
UIB	Upper Indus Basin
WAPDA	Water and Power Development Authority
WEAP	Water Evaluation and Planning

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CHAPTER 1

INTRODUCTION

Water management has become more complex with human population growth, the emergence of broader performance objectives, and the increase in uncertainty of water availability, energy demand, and flood risk (Rogers et al. 2005, Somlyódy and Varis 2006). With the world's population expected to rise to 9 billion by 2050, sustainably meeting food needs will require a 60% increase in agriculture production and lead to an estimated increase of global water withdrawals by 13% (Rost et al. 2008, De Fraiture and Wichelns 2010, Valin et al. 2014). This increase in water demand is projected to result in demand exceeding supply in 60 of the world's largest economies, affecting 57% of the global economy and 74% of global agriculture production (Turner 2004). Similar to agriculture needs, energy consumption is expected to increase by 40% by 2050, especially in the Middle East, India, and China (Grafton et al. 2016, Liu et al. 2016). A direct connection between water management and energy is hydropower, which currently supplies 20% of the global energy demand with a future target of 33% (Burrett et al. 2009). Changes in water availability, such as drought, are likely to increase the criticality of hydropower generation in Asia the most, with significant impacts in North America, Europe, and other continents (van Vliet et al. 2016). In addition to water supply and hydropower challenges, water managers are faced with increased flood risk. Over the past few decades, numerous countries have experienced massive flooding affecting large fractions of their populations, including among the worst recorded floods in Europe (1993), India (1996-1998), Bangladesh (1998), Pakistan (2010), and China (2010) (Giorgi et al. 2004). The global concern with the increased challenges facing water management is that more than 50% of the world's population lives in seven countries anticipated to be affected the most, four countries of which are in Asia.

In South Asia, Pakistan is facing grave challenges of increasing population, increasing water extremes, and elevated and broadened expectations for water system performance. Once an abundant water country, Pakistan has now become a water-stressed country and is estimated to become water scarce by 2025 (Rijsberman 2006). The agriculture sector, which accounts for 26% of the Gross Domestic Product (GDP), is the largest water user consuming about 93% of total water withdrawals (Rasul 2014). Agriculture in Pakistan is under pressure to feed a population of more than 200 million (Mahmood et al. 2009). With a growth rate of 2%, annual food production is projected to double by 2042, which would increase water requirements by 40% (Kahlown and Majeed 2002). Similar to agriculture, the energy sector of Pakistan is also facing a severe crisis. The total installed energy generation capacity is approximately 25,000 megawatts (MW), of which hydropower provides 33% (Mirza et al. 2008). The average shortfall of supply is 4,000 MW, with a maximum of 6,000 MW reached in 2007 (Mirza et al. 2008).

Floods and droughts significantly affect agriculture and hydropower in Pakistan. Floods have occurred more frequently, and over the last 50 years, a third of all natural disasters in Pakistan were from floods (Siegmann and Shezad 2006). The inundated area of flooding typically includes the Punjab and Sindh Provinces (termed the Lower Indus

Basin), which accounts for 74% of the total agriculture production and 83% of the total energy consumption (Siegmann and Shezad 2006). Although not occurring as often as floods, droughts in Pakistan have increased in frequency from three drought years in a period of ten to four out of every ten years (Roy 2007). The consecutive drought years from 1997-2001 were the worst recorded in Pakistan, causing severe losses to agriculture production (Majeed et al. 2002). During these years, the overall agriculture growth rate of Pakistan was between 2.6% and 10% for the major crops of wheat, cotton, and rice (Ahmad et al. 2003).

These water challenges, occurring due to excess or lack of water, provide incentives for improvement in water management, and thus opportunities. Water management for irrigation supply, hydropower generation, and flood control in Pakistan is predominantly provided by three large reservoirs (Tarbela, Mangla, and Chashma) operating with an interconnected system of barrages (structures on the rivers to divert water) and canals. Among the three reservoirs, Tarbela is the most critical and important reservoir because it contributes to 35% of annual irrigation supply and 72% of hydropower generation in Pakistan. In addition, barrages downstream of Tarbela Dam are at risk of medium (discharge higher than 200,000 cfs and less than 400,000 cfs) to high flooding (discharge higher than 400,000 cfs) (Khan et al. 2011). Given the importance of Tarbela, significant gains in agriculture production, hydropower generation, and flood control in Pakistan may be possible with strategic changes in the operations of the reservoir.

Tarbela Reservoir on the Indus River serves multiple purposes, most importantly irrigation supply, hydropower generation, and flood control. To meet the objectives, the reservoir is operated following a rule curve that defines the desired water surface elevation (and thus stored water volume) of the reservoir at a given time. Releases from the reservoir are then set by the water managers to target the desired water surface elevation (WAPDA, 2016).

Tarbela Reservoir is divided into four storage zones: (1) inactive, (2) conservation, (3) flood control, and (4) surcharge, each targeting a set of objectives as is typical of reservoirs (Liu et al. 2011). In the inactive zone, water releases or withdrawals are not made, so water is evaporated and lost through seepage. The conservation zone targets meeting irrigation demand and hydropower generation, and active releases from this zone are set to meet these objectives. The flood control zone is usually empty, except during flood events when the storage is filled in an effort to reduce downstream flood impacts. The surcharge zone is operated in flood stage to pass water to the spillways (Lindström and Grani 2012). The current operations of Tarbela lead to conflicts in storage and release from the conservation and flood control zones when considering multiple objectives. For instance, the irrigation supply objective is maximized by setting releases so the reservoir is at its lowest level in May and June and its highest level in August and September to store water for use in the low flow months of January and February. With low reservoir levels in May and June, the hydropower generation objective is negatively impacted when power is greatly needed. Furthermore, with the high water levels in August, the flood control objective is hindered by lack of storage capacity.

The primary problem is the operations of Tarbela Reservoir are guided primarily on achieving a single objective of maximizing irrigation supply. Further, the criterion for performance is limited to the reliability of meeting the irrigation supply. This singular view of objective and performance criterion does achieve positive benefits for irrigation.

However, there is an opportunity to improve performance for other objectives and improve performance for other criteria, such as considering resilience and vulnerability in addition to reliability (Hashimoto et al. 1982). The use of a single performance criterion (e.g., reliability of irrigation supply) is common for reservoir operations, but it is known to be limited in describing the strengths and weakness of the reservoir operations (Moy et al. 1986, Vogel and Bolognese 1995). Improvement in operational performance is likely if decisions can consider multiple criteria, and in particular reliability, resilience, and vulnerability (RRV) (Jain and Bhunya 2008).

Following from other studies, it is expected that the performance of Tarbela Reservoir can be enhanced by altering operations to consider RRV criteria and targeting hydropower generation and flood control objectives in addition to the irrigation supply objective (Li et al. 2010, Giuliani et al. 2016, Mateus and Tullos 2016). Therefore, the goal of this research was to improve the performance of Tarbela Reservoir. The objective was to explore the effect of alternate operations on the reliability of water supply for irrigation and hydropower, and to identify the alternate operation resulting in the highest reliability. With the alternate operation / proposed rule curve and using a multicriteria evaluation approach, performance was evaluated under historical and future conditions. Based on preliminary considerations, it was hypothesized that shifting the targeted low storage volumes in the reservoir earlier in the calendar year would lead to improved RRV for three target objectives of irrigation supply, hydropower generation, and flood control. The study entailed applying a computer model to simulate the performance of Tarbela Reservoir and calculating the RRV criteria for historical and projected future climate and water demand conditions. The iterative investigation of rule curves and calculated performance sought to improve all criteria for all objectives.

CHAPTER 2

DESCRIPTION OF STUDY AREA

2.1 Indus River

The Indus River emerges from the Tibetan Plateau, enters the north-eastern part of Pakistan, flows through the dry alluvial plains of Punjab and Sindh, and drains into the Arabian Sea. The catchment area of the Indus Basin contributing to the Tarbela Reservoir (the only controlling structure on the Upper Indus River) is 63,650 mi^2 (Mukhopadhyay and Khan 2014). The area is predominantly a barren and glaciated landscape (Khan et al. 2014). The climate in the Indus River Basin varies significantly throughout the year. Upstream of Tarbela Dam is considered arid and downstream semi-arid. Mean temperature in the Indus Basin ranges from 35.6° F during winters, and 120.2° F during summers (Fowler and Archer 2006). Evaporation is high with average values ranging between 65 in and 80 in per year (Bastiaanssen et al. 2002). Mean annual rainfall is low, ranging from 3.5 in to 20 in (Archer and Fowler 2004). The Indus River provides the essential water for irrigated agriculture in Pakistan, which is the prime driver of Pakistan’s economy.

The flow in the Indus River is primarily from snowmelt and glacial melt (Mukhopadhyay and Khan 2014). The mean annual flow of the Indus at Besham Qila, located 50 miles upstream of Tarbela Reservoir, is 82,526 cfs (WAPDA, 2017a). The river flow is highly variable with a standard deviation of 87,285 cfs and recorded low and high flows of 8,900 cfs (March 7, 2002) and 710,100 cfs (July 30, 2010), respectively (WAPDA, 2017a). The historical mean monthly inflow shows typical high interannual variation with about 84% of the annual inflow arriving from May to September (Cook et al. 2013) (Figure 2.1). Tarbela Reservoir is operated to manage the variability in the timing and magnitude of the flows and provide a substantial degree of regulation for the releases to achieve irrigation supply.

2.2 Tarbela Dam and Reservoir

The Tarbela Dam, constructed in 1976 on the Indus River, was a result of the Indus Waters Treaty (IWT), which was signed between Pakistan and India in 1960. Since independence in August 1947 and prior to the implementation of this treaty, both countries had serious disagreements over the flow of the eastern (Ravi, and Sutlej) and western (Chenab, Jhelum, and Indus) rivers of Pakistan (Nazakat Ali 2015). Pakistan being the lower riparian, whose economy was largely dependent on agriculture, had to rely on the

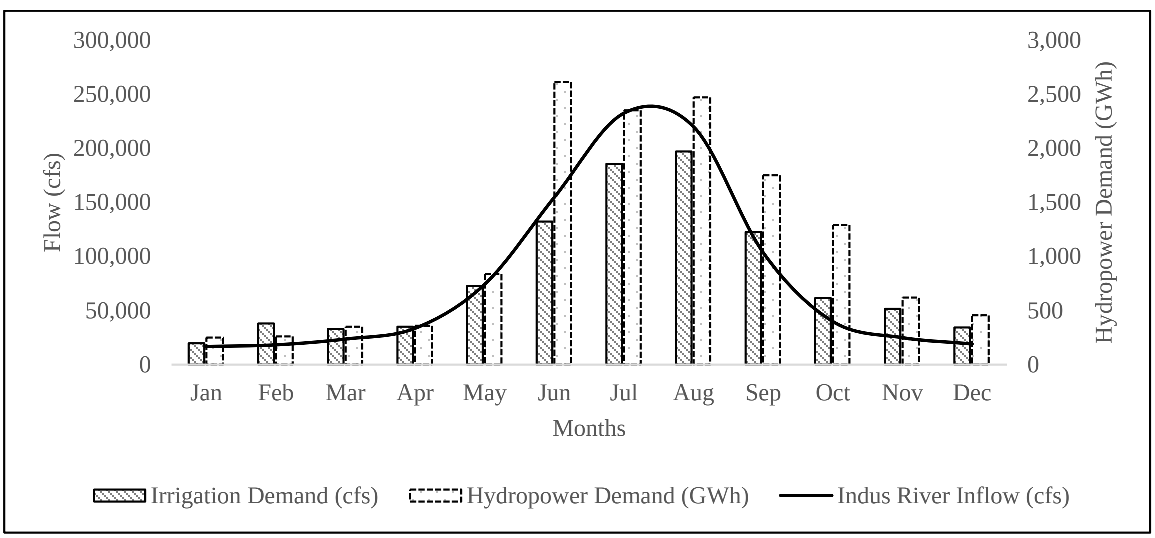

Figure 2.1 Mean Monthly Inflows, Irrigation and Hydropower Demand

unregulated flows from the neighboring country. The World Bank facilitated the negotiations between the two countries for ten years, which concluded with the signing of the IWT (Alam 2002). The IWT gave exclusive rights to use the water of the eastern rivers to India, while the rights to the water in the western rivers were assigned to Pakistan (Nazakat Ali 2015). The IWT had provisions to construct three storage reservoirs, namely Tarbela, Mangla, and Chashma, six barrages, and eight link canals to mitigate the effect of the loss of water due to the restriction on the flows of the eastern rivers (Tariq 2010). The construction of the reservoirs, especially Tarbela (referred to as ‘a dam on the Indus’ in the treaty), facilitated Pakistan to move toward water security, enabling its irrigation and hydropower generation entirely independent of India.

Besides the primary function of mitigating the effect of loss of water from the eastern rivers and providing a firm base for the development of the irrigation system, a subsidiary goal was also introduced during the planning phase, which included hydropower generation to meet the country’s increasing energy demand at the time. The Bara site, as shown in Figure 2.2, was selected to meet the objectives of the project because of its higher storage capacity, favorable topography, and lower cost. The initial design of the Tarbela Dam had no provisions and guidelines for flood control. Flood regulation became an incidental aspect of Tarbela, providing limited flow regulation during the flooding season from July through August.

The initial design of the project consisted of a dam body rising 486 ft above the ground level, crest length of 9,000 ft, lake/reservoir volume of 11.1 MAF, and had four tunnels.

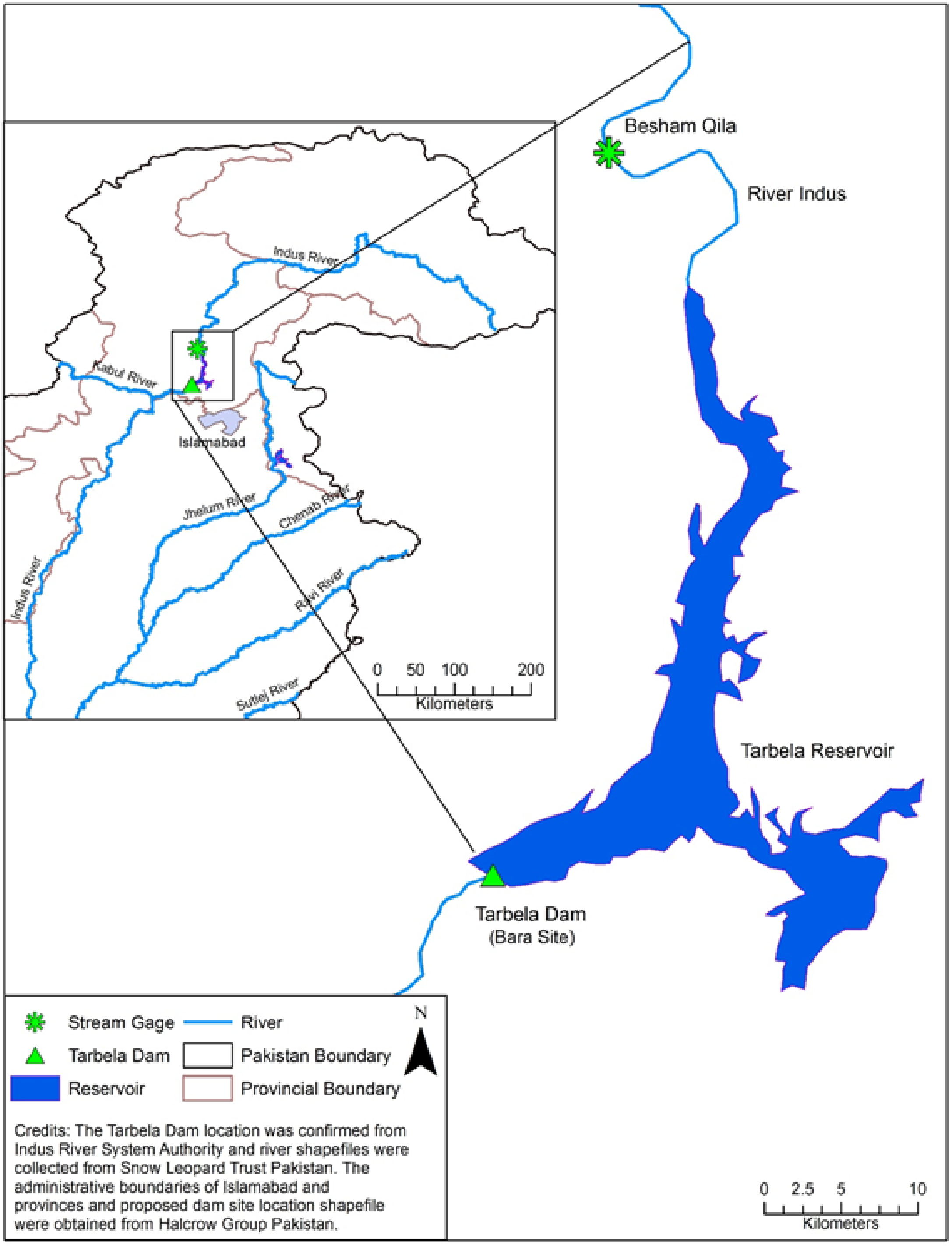

Figure 2.2 Location Map of Tarbela Dam and Reservoir

WAPDA, during the planning stage, estimated sedimentation yield and expected releases from Tarbela Reservoir. The expected releases were the projected releases to fulfill the water requirement for irrigation purposes, which were based on the command area adjusted for the effect of sedimentation consuming live storage in the reservoir. During the period of operation from 1975-1990, the actual releases from Tarbela for irrigation supply exceeded projected releases by 20.1% (calculated after every five years) and from 1990-1998 by 23.4% (calculated after every two years) (Survey and Hydrology, OM&M, TDP, WAPDA, 1999). The increased actual releases are the only indicator representing the performance of Tarbela, which has been increased by a lower than projected sedimentation yield. The lower sedimentation yield increased the available water storage in the reservoir, in turn increasing water available for release to meet irrigation demand. The percentage increase from the projected releases does not reflect 100% reliability of water supply for irrigation because the command area (irrigated agriculture lands) has gradually increased by 39.4% (Agricultural Statistics of Pakistan, 2017).

Similar to the planned releases for the irrigation supply, WAPDA also estimated the hydropower generation from Tarbela. From 1975-1992, the actual hydropower generation was lower than the projected hydropower generation by an average of 4,729 GWh per year (calculated after every year). From 1993-1998, the actual hydropower generation was more than the projected by 1,720 GWh per year because of the full development of hydropower generation units in the tunnels. The hydropower generation does not meet Pakistan’s hydropower demand and does not represent the potential amount that can be generated by Tarbela (the average shortfall of generated versus potentially generated is on average 4,500 MW).

Flood control was an incidental outcome of Tarbela Reservoir because no provisions were made in the original design. However, within the current reservoir operations, limited attenuation of flood peaks are provided to avoid the incidence of high peaks in the downstream locations, where flood conditions occur if the flow is above 400,000 cfs. From the limited data shared by WAPDA, peak flows in July 1988, July 1989, August 1992, and August 1995 were reduced by 21.3%, 26.5%, 43.1%, and 2.4%, respectively.

Since the commissioning of Tarbela Dam in 1976 until 2013, a loss of 30.6% of storage capacity and increased water and hydropower demands from the project has not led to substantial changes/revisions of the reservoir operations. Irrigation requirements still dictate the releases from the reservoir.

2.3 Current Reservoir Operations of Tarbela

Tarbela is a large multipurpose reservoir whose operations rules are set according to the irrigation requirements of the provinces. Over the period of 1976 to 1993, the lack of a water sharing agreement between the provinces led to ad hoc operations of Tarbela Reservoir. In 1991, the provinces signed a formal accord, which resulted in the creation of the Indus River System Authority (IRSA) in 1993. IRSA is now the designated body responsible for water allocation among the provinces based on agreed indicators of the provincial allocations, which are dependent on the average river flows. The indents (water requests) submitted by the provinces form the basis of the outflows from the reservoir, which over the operational period of Tarbela resulted in the development of the rule curve. The rule curve developed by WAPDA (Figure 2.3) shows that the reservoir should be

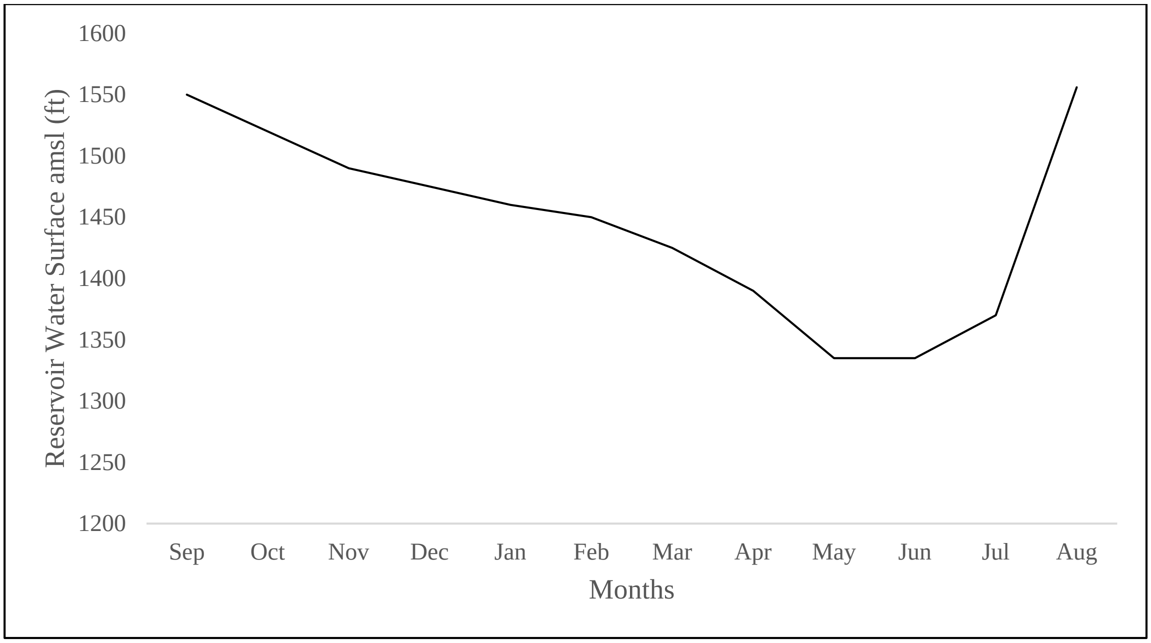

Figure 2.3 Existing Rule Curve for the Tarbela Reservoir

lowered to the minimum level of 1300 ft amsl by the middle of May until 20th of June to maximize releases for irrigation demand. The maximum level of 1550 ft amsl is the target for mid-August after attenuating the high flood peaks in July and early August. The filling should be at an average rate of 9.8 ft/day up to 1510 ft amsl and 1 ft/day from 1510 ft amsl to 1550 ft amsl. The filling rates were established by considering the structural integrity and safety of Tarbela Dam. At 1550 ft amsl (maximum conservation level), the flood is routed through the spillways, which have the capacity of 1,499,320 cfs. The designed flood of 1,774,350 cfs and a maximum flood of 2,128,627 cfs is routed through the existing outlet facilities (tunnels and spillways) with a surcharge (water depth) of 1.9 ft and 6.9 ft (above the maximum conservation level of 1,550 ft amsl), respectively. The drawdown of the reservoir should be by the indent provided by the provinces to the IRSA. The downstream flow from Tarbela Reservoir should not exceed 400,000 cfs as higher flow results in flooding.

The current operations of Tarbela Dam have a number of embedded limitations, which are summarized here:

(1) Single Objective: The rule curve is based on a single objective, meeting irrigation water needs. This uni-target approach neglects other objectives, such as hydropower generation. Although Tarbela contributes approximately 57 MAF (35% of total irrigation water need) per year to meet irrigation demand, the hydropower dependency on Tarbela is also high (Haq and Abbas 2006). According to WAPDA, Tarbela is responsible for generating 72% of the country's hydropower needs, which contributes 3,780 MW. Moreover, hydropower demand of the country is expected to increase by 7.9% each year in the near future (Khan and Ahmad 2008). Therefore, reservoir operations should consider hydropower generation as an objective in addition to irrigation supply.

(2) Single Criteria: Reservoir performance is only based on the reliability of meeting irrigation demands. Consideration of resilience and vulnerability would improve overall benefits.

(3) Operational Limitation of Controlled Release: According to the WAPDA, the releases from Tarbela exceeding 400,000 cfs are considered a flood situation. There were 13 events between June 1976 and December 2013 where releases from Tarbela exceeded the threshold value of 400,000 cfs. Due to the rule curve dictating higher reservoir levels in August, flow passes through the spillway.

Annually, over 70% of water discharged at Tarbela is through the spillways, which are not used for hydropower generation (WAPDA, 2017a).

(4) No Future Climate Change Consideration: The operations of Tarbela Dam do not include adaptation for projected streamflow changes in the future. The Tarbela Reservoir is located in the Upper Indus Basin (UIB), which contributes more than 50% of the annual flow in the Indus River (Bookhagen and Burbank 2010, Lutz et al. 2014, Mukhopadhyay and Khan 2014). The UIB is considered a climate change hotspot because of the projected variability in precipitation, snow and glacier melt, and expected intra-annual variation of Indus River streamflow (Reggiani and Rientjes 2015). The variability of inflows is affecting the live storage volume in the reservoir, which already has a low storage coefficient of 0.11 (ratio of live storage to the mean annual inflows). This makes it difficult for the IRSA to meet the indent requirements of the provinces from the reservoir, which has a very high draft ratio of 0.97 (ratio of annual demands to the mean annual inflow).

CHAPTER 3

METHODOLOGY

3.1 Overview

This research study was divided into three parts. First, a computer model was created using the Water Evaluation and Planning (WEAP) System. This model was verified using available data. Second, the WEAP model was used to iterate through an analysis of the effects of altering the existing rule curve. The outcome of the second part was a proposed rule curve to improve performance across the RRV criteria and the three objectives of irrigation supply, hydropower generation, and flood control. The third part of the research was to test the proposed rule curve under historical and future conditions. The WEAP model was applied again to test the proposed rule curve. Two WEAP models were developed, one with the current operations and the other with the proposed operations. Each model was given two conditions, climate (inflow) and irrigation demand, for historical (June 1976-December 2013) and future (January 2014-December 2050) periods. As shown in Figure 3.1, the evaluation of the proposed rule curve was then based on comparing current operations and proposed operations under historical and future conditions. The system performance measures (RRV) were computed for each objective, and the results analyzed over the entire period (historical and future) and type of water year (high, medium, and low flow).

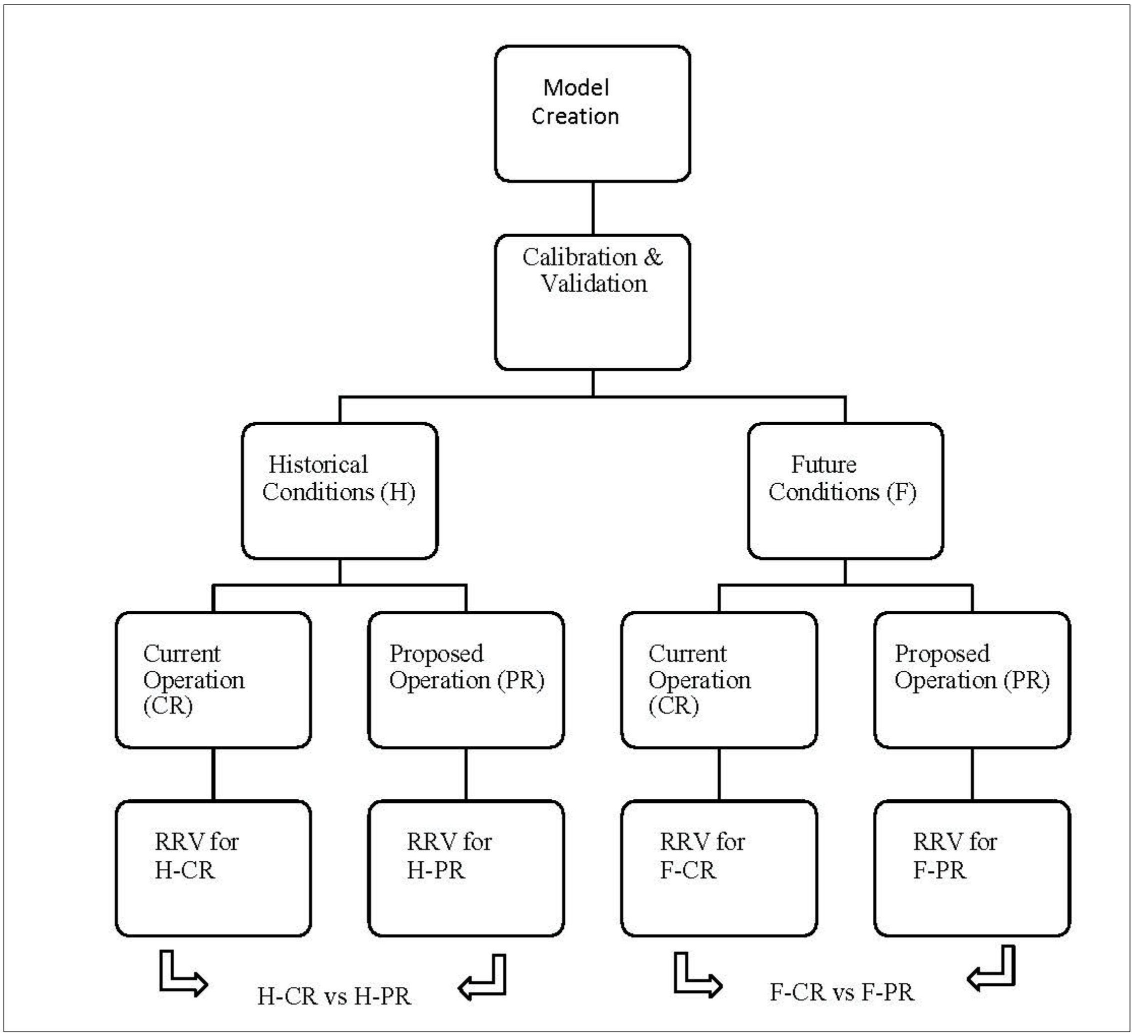

Figure 3.1 Overview of the Methodology

3.2 The Water Evaluation and Planning (WEAP) System Model

WEAP is a well-established modeling tool for executing simulations to inform water resources planning and management at the community to river-basin scales (Yates et al. 2005). WEAP has two primary functions (Mounir et al. 2011):

(1) Simulation of natural hydrological processes (e.g., evapotranspiration, runoff, and infiltration) to enable assessment of the availability of water within a catchment.

(2) Simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (i.e., consumptive and non-consumptive water demands) to enable evaluation of the impact of human water use.

River basin system model development in WEAP can be divided into four parts: (i) water sources (river, groundwater, other supply, catchment, and runoff); (ii) water withdrawals (reservoirs, transmission links, and water treatment plants); (iii) water demands (demand sites and flow requirement); and (iv) model verification, calibration, and validation. Typically, in WEAP, the upstream flow of the river is represented by measured flows or the hydrologic response of a defined catchment area. Reservoirs are placed on the river and restrict flow by regulating releases according to defined reservoir operations. River reaches carry releases from the reservoirs to demand sites. WEAP performs a balance of flow from the upstream flow of the river to the demand sites, making allowance for inflows, storages, and subtractions in between. The model allocates the water availability to designated uses based on a user-defined ‘priority’.

WEAP has been extensively used to investigate historical and future simulations of water demand and supply, structural and operational changes in the reservoirs, irrigation supply requirement, hydropower generation requirements, inflow stream constraints, evaporation, infiltration, and crop requirement (Sieber 2006). These simulations are created under scenarios of varying demand changes, infrastructural changes, and climate change to facilitate water managers and policy makers in decision making (Purkey et al. 2007). For instance, WEAP was used as a simulation tool to investigate the changes in Xinánjiang-Fuchunjiang Dam operations in China as an adaptation strategy for future changes in water supply and demand (Vonk 2013). The study concluded that recommended operations reduced the shortage index by 72%, but was unable to completely mitigate the impact of climate change and socio-economic development. By using the WEAP platform, a number of studies have evaluated the performance of water resource systems under climate change (Hall and Murphy 2010, Kiparsky et al. 2014). Hall and Murphy (2010) developed a WEAP model for the Moy catchment in Western Ireland to analyze the vulnerability of water infrastructure under changing climate conditions. The analysis suggested the water supply infrastructure is vulnerable to being under water stress conditions in the future. (Kiparsky et al. 2014) studied the Tuolumne and Merced River Basins, California and found increased air temperature reduced water supply reliability from 0.84 to 0.75. WEAP has also been used for assessment of shortfalls in water supply under infrastructure expansion scenarios (Alemayehu et al. 2010). The study conducted for Lake Tana in Ethiopia concluded future expansion of irrigation schemes, 548,852 AF/yr, would reduce the mean annual water level of the Lake by 1.44 ft. The aforementioned studies note WEAP's ability to be reliably applied at different spatial and temporal scales to address a variety of issues, in particular, to test adjustments in decision parameters and inform policymaking.

For the present study, a representative model was created for Tarbela Dam and Reservoir using WEAP. The Indus River was added as a 'river' in the WEAP model. Although WEAP allows the use of a shapefile to trace the course of the river, the Indus River was not traced accordingly. A reservoir node was added to the Indus River, which represents the Tarbela Dam and Reservoir. A reference 'streamflow gauge' node was added downstream of the reservoir, as a 'release measurement', for model calibration and validation purposes. A demand node was added further downstream that represents the agricultural water demand from the reservoir. The model schematic is shown in Figure 3.2.

3.2.1 Data Collection and Input

The daily inflow, demand, and physical data for reservoir and release measurements were obtained from WAPDA, the operating authority of the Tarbela Reservoir (WAPDA, 2017a). The data range covers the period from June 1976 to December 2013. The quality of data acquired from WAPDA was divided into three categories: 'verified', 'acceptable' and 'uncertain'. The 'verified' data refers to recorded, documented, and verified data managed by WAPDA. The 'acceptable' quality of data was recorded and documented, but not verified, and the 'uncertain' quality of data refers to data not documented or verified

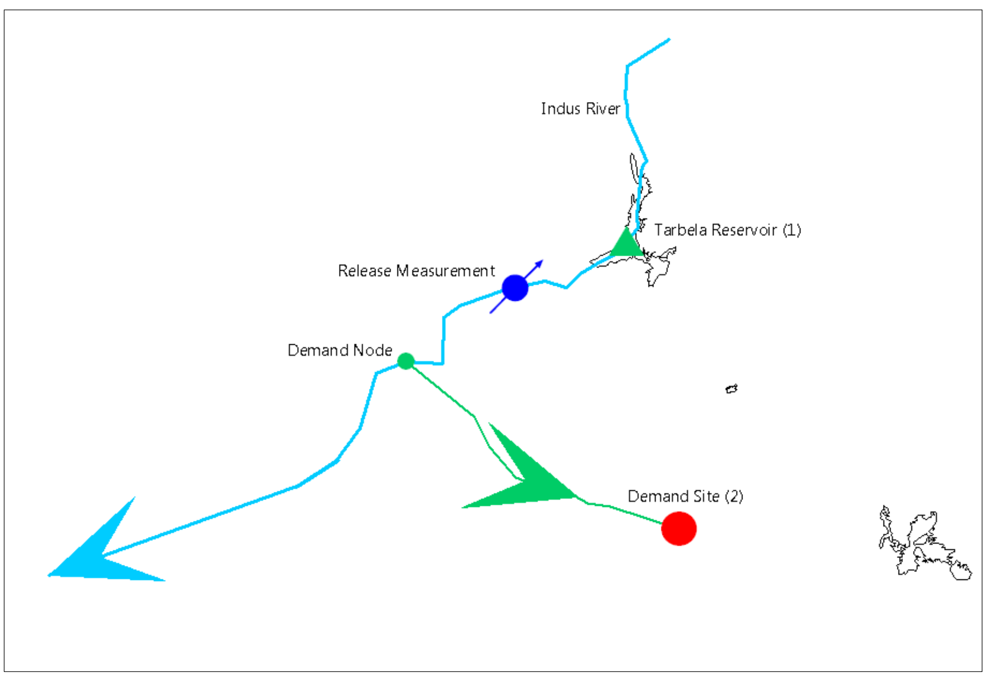

Figure 3.2 Overview of WEAP Model Representing Tarbela Reservoir on the Indus River

by WAPDA. As the WEAP model of Tarbela is demand driven, it was very important to have very accurate inflow, demand, and physical data of the reservoir. The daily inflow and demand data were of ‘verified’ quality. The physical data for the reservoir were mainly comprised of ‘verified’ quality, except evaporation, which was of ‘acceptable’ quality.

Tarbela Dam and Reservoir were modeled by describing the physical, operation, hydropower, cost, priority in WEAP. The parameters, their significance, data values, and quality of data for the parameters, as provided by WAPDA, is summarized in Appendix A.

3.2.2 Model Calibration and Validation

The streamflow gauge, added as a ‘release measurement’ in the model, downstream of Tarbela Dam was used to calibrate the model. The calibration was based on the comparison of the actual releases, added in the ‘release measurement’ node, to the WEAP model releases. The calibration period from June 1976 to December 2001 was selected as a representative record of the entire 1976 to 2013 simulation period, considering mean annual flow and extreme events. During the period from June 1976 to December 2013, mean annual flow of the Indus was 82,526 cfs with a standard deviation of 9,546 cfs. During the selected calibration period (June 1976-December 2001), mean annual flow was 83,096 cfs with a standard deviation of 10,091 cfs. Also, during the historical record (June 1976-December 2013), there were fourteen floods and five drought events, making a total of nineteen extreme events. During the selected calibration period (June 1976-December 2001), there were five floods and the same number of drought events. Therefore, the calibration period contained a sufficient number of extreme events. The model input parameters, provided in Appendix A, were of ‘verified’ quality, except evaporation, which was of ‘uncertain’ quality. Therefore, the model was calibrated by changing the least certain input variable, which was evaporation. The average evaporation values for the calibration period (84.6 in) was representative of the historical record (86.9 in). The calibration was done by using an inbuilt WEAP calibration tool known as ‘PEST calibration’. In the PEST tool, the parameter to calibrate was selected as evaporation in the ‘add data variable’ user input form, and the range to modify this parameter was selected as 90% increase and a decrease of the base value (0.02 ft/day) with an increment of 10%. Starting with 90% decrease in the evaporation to 90% increase in the evaporation value, and with selecting ‘Auto Calculate’ for the result, nineteen different reservoir release time series were computed downstream of the dam where ‘release measurement’ node was added in the model. The hydrograph of the nineteen model releases was compared with the actual/observed releases, recorded at the same node in the model. To calculate the accuracy of the observed data and model data, the Nash-Sutcliffe Efficiency (NSE) Index was used:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Qm - Qo)^2}{\sum_{t=1}^{T}(Qo - \mathrm{Qa})^2}$$

where Q_m, Q_o, and Q_a represent model discharge, observed discharge, and mean of observed discharge, respectively. The NSE value close to 1 shows that the accuracy of the model is high (Nash and Sutcliffe 1970). The time series of the releases from the model with the increase in the evaporation by 30% (0.026 ft/day) resulted in the highest NSE index of 0.77. Therefore, 30% increase in the evaporation was selected as the chosen value for calibration. The timing of the model peaks matched well with the observed discharge values. However, the magnitude of the peak values is higher than the observed discharge values. Figure 3.3 shows the hydrograph of the observed releases with the modeled releases.

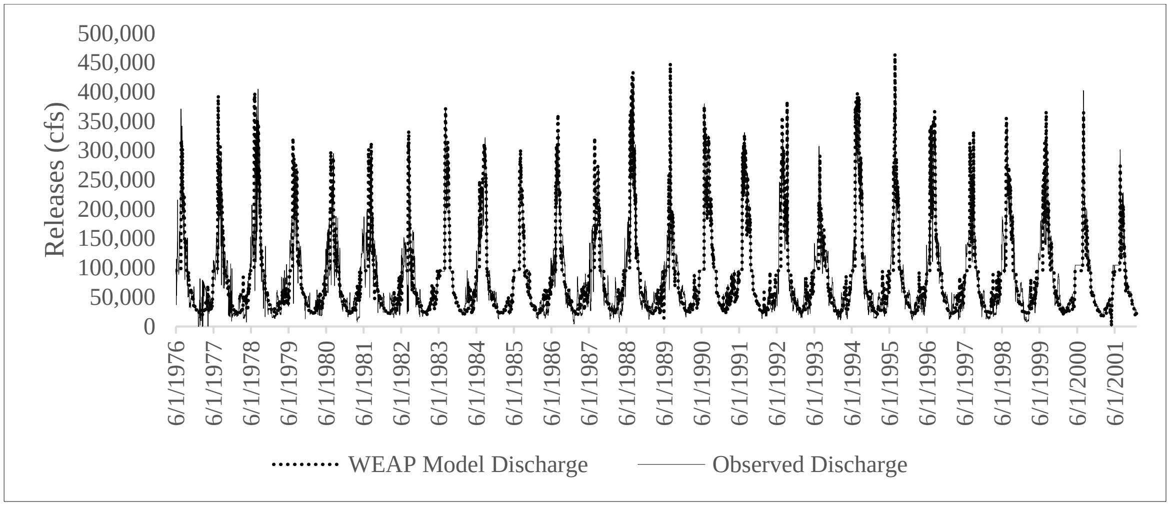

Figure 3.3 Hydrographs of the Observed and Simulated Releases Showing Calibrated Model Fit

The validation period was selected from January 2002 to December 2013. The validation results showed the NSE index value as 0.74. As observed with the calibration, the timing of the model peak matched with the timings of the observed discharge, but the model peak was higher than the observed peak values (Figure 3.4).

After developing, calibrating, and validating the model with the current operations under historical conditions, the next step was to explore the effect of altered reservoir operations on performance.

3.3 Exploration of Altered Reservoir Operations

The proposed altered operations of Tarbela Dam were developed by changing the target water surface elevations in the reservoir (i.e., the rule curve) with the intent of improving the performance under historical and future conditions. The proposed altered operations to explore were guided by the following observations of current operations:

(1) Under current operations, the water level in the reservoir is maintained at the

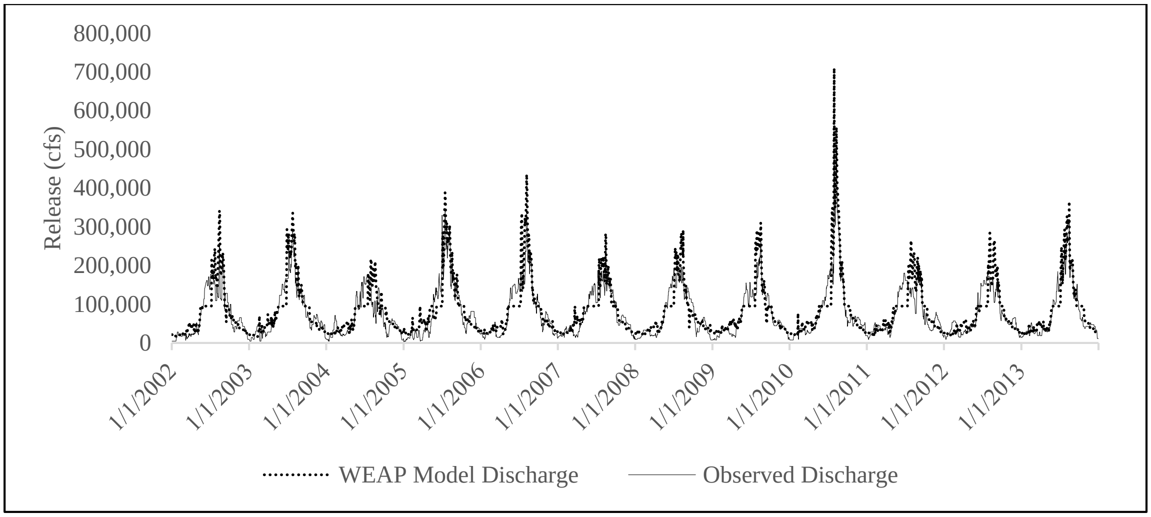

Figure 3.4 Hydrographs from Observed and Simulated Releases for Validation Period

minimum from mid-May to mid-June. During this month period, water demand and hydropower generation requirements are high. By maintaining the reservoir water surface level at the minimum, the water releases are maximized, but at the expense of hydropower generation potential. Therefore, one proposed altered operation change is to adjust the timing of the minimum reservoir level earlier. The rule curve can thus be modified, but adhere to two constraints. First, the maximum reservoir level should be targeted for late August, because of high flows during July and August. Second, the proposed earlier drawdown of the reservoir must follow the water indent requirements from the provinces. Figure 3.5 shows the resulting set of rule curves with varied minimum reservoir levels. Using WEAP simulations, the recommended rule curve can be chosen based on identifying the one that produces the highest reliability for irrigation supply and hydropower generation.

(2) Since flood control will not be addressed by the proposed changes in the timing

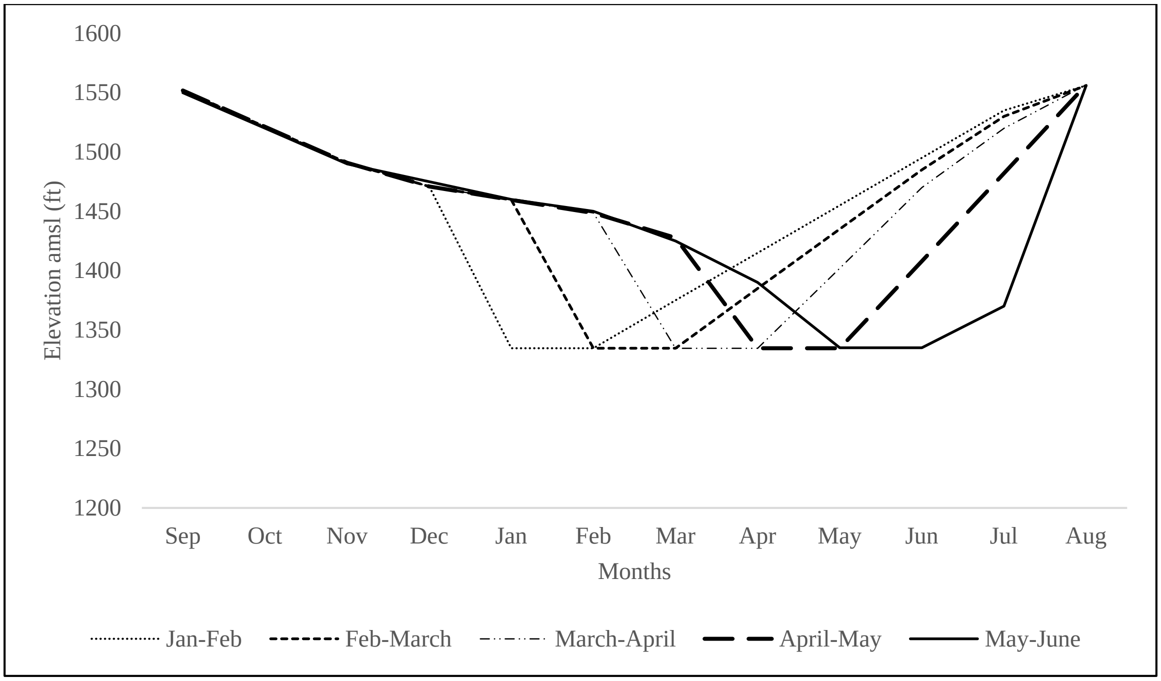

Figure 3.5 Rule Curves with Different Period of Minimum Reservoir Levels

of the minimum water level or other changes in the rule curve, structural changes to upgrade the capacity of the tunnels (increasing maximum hydraulic outflow) was investigated. The increase of maximum hydraulic outflow capacity had no effect on the reliability of water supply for irrigation and hydropower generation, which was calculated by changing the minimum water elevation in the reservoir.

To increase the flood reliability with the proposed rule curve, capacity of irrigation tunnels was increased from 173,000 cfs to 400,000 cfs. The maximum hydraulic outflow was chosen based on maximizing the flood control reliability.

3.4 Performance Evaluation of Proposed Operations

The performance evaluation of the proposed altered operations compared to current operations was evaluated on the following bases:

(1) Entire Period (Historical and Future): The performance evaluation (RRV of each objective) of proposed operations is based on comparing current operations and proposed operations under historical and future climate (inflow) and irrigation demand: current operations (CR) vs. proposed operations (PR) under historical climate and demand conditions (H) (H-CR vs. H-PR), and current operations vs proposed operations under future climate and demand conditions (F) (F-CR vs. F-PR). The future conditions refer to unforeseen inflow and irrigation water demand conditions. The period for the future conditions was from January 2014 to December 2050. The number of years in the future was the same as that used for the historical conditions because the future conditions were not exactly calculated but assumed as varying ranges between -90% to 90% (10% interval) of the historical conditions. Based on the previous studies, this range of future conditions fills a range of climate and demand conditions including plausible and extreme conditions, i.e., extreme floods and droughts and very high and low irrigation water demands (Ray and Brown 2015).

(2) Type of Water Year: For this analysis, the performance of the reservoir with proposed operations over the current operations were evaluated on the basis of the type of water year for the historical record (June 1976- December 2013). The historical annual inflows upstream of Tarbela Reservoir were divided into three categories: (i) low flow water year, where the average annual flow is less than 75,449 cfs (25^{th} percentile); (ii) medium flow water year, where the average annual flow is greater and equal to 75,449 cfs but less than 89,871 cfs (25^{th} -75^{th} percentile); and (iii) high flow water year, where the average annual flow is

greater than 89,871 cfs (75th percentile). The analysis was performed to determine the performance of proposed operations on the basis of critical climate combinations, i.e., low flow period for hydropower generation and irrigation demand and high flow for flood control.

Three performances indices, viz. reliability, resilience, and vulnerability, were used for performance evaluation.

(1) Reliability: Water for irrigation supply and hydropower generation reliability for each scenario were calculated internally in WEAP. WEAP calculates the reliability as:

$$\text{Reliability} = \frac{Number\ of\ time\ periods\ of\ zero\ shortage}{Total\ Time\ Period}$$

For water supply and hydropower reliability, the time period of zero shortage means when sufficient volume of water was supplied to the demand node and the turbines for hydropower generation. The flood control reliability was externally calculated on the basis of the same definition of reliability as used for water supply and hydropower, by exporting the 'release time series' from WEAP. For flood control reliability, time period of zero shortage refers to the days when the releases from the reservoir were less than 400,000 cfs.

(2) Resilience: The irrigation supply and hydropower generation resilience were calculated externally by exporting the 'supply delivered' and 'hydropower generation' data from the Result view in WEAP. The actual 'irrigation demand' and 'hydropower demand' and the exported excel sheets of 'supply delivered' and 'hydropower generation' were used to determine the number of times the system follows a failure state from the satisfactory state and number of days the

system was in the failure state. The failure state was defined as when the required volume of water could not be released from the reservoir for irrigation demand or hydropower generation. The frequency of a satisfactory state following an unsatisfactory state is the basis of resilience:

$$\text{Resilience} = \frac{Number\ of\ times\ a\ satisfactory\ state\ follows\ an\ unsatisfactory\ state}{Number\ of\ unsatisfactory\ value\ occurs}$$

The flood control resiliency was calculated externally by exporting the ‘reservoir release data’ from WEAP. The number of days with the satisfactory state (release less than 400,000 cfs) followed an unsatisfactory state (number of days when the flow is exceeding 400,000 cfs), and number of days releases exceeding the threshold values were calculated and used in the above equation.

(3) Vulnerability: The vulnerability of irrigation supply, hydropower generation, and flood control was also calculated externally by using the following equation:

$$\text{Vulnerability} = \frac{Sum\ of\ Positive\ values\ of\ (target - delivery)}{Number\ of\ times\ an\ unsatisfactory\ value\ occurs}$$

The performance evaluation for the entire period with proposed operations over the current operations was calculated as the percentage improvement in the system performance for each objective with proposed operations.

Percentage improvement in performance with proposed operations for any objective =

$$\frac{('H-PR'\ Rel)-('H-CR'\ Rel)}{H-PR}$$

Positive values show the improvement while negative values show a decrease in the performance indices of the objective. The above equation can be substituted for future scenarios (F-CR vs. F-PR) and performance measures (resiliency and vulnerability).

CHAPTER 4

RESULTS

4.1 Effect of Rule Curve Changes on Reliability

The simulations in the WEAP model with altered rule curves under the historical conditions showed that the reliability of hydropower and irrigation supply was very sensitive to the changes in the minimum level (Figure 4.1). With the existing minimum reservoir level during May-June, improvement in irrigation demand was conflicting with the hydropower generation, because maximum releases were made to fulfill the irrigation objective, lowering the reservoir elevation and thus reducing potential hydropower generation. In general, 63% of large reservoirs, on a global scale, have a conflict between irrigation and hydropower generation reliability (Zeng et al. 2017). These reservoirs are mainly located in Central U.S., Northern Europe, Central Asia, India, and Pakistan (Chatterjee et al. 1998, Kadigi et al. 2008, Yang et al. 2016). The reasons for the conflict in Pakistan are that (i) storage capacity of the reservoirs, especially Tarbela, is not large enough to properly regulate the streamflow to meet both hydropower and irrigation demands, and (ii) although the timing of hydropower and irrigation demands are the same, releases are not made accordingly (Zeng et al. 2017).

As shown in Figure 4.1, the proposed change in the minimum level from May-June to April-May is seeking to establish a better complement of hydropower generation and

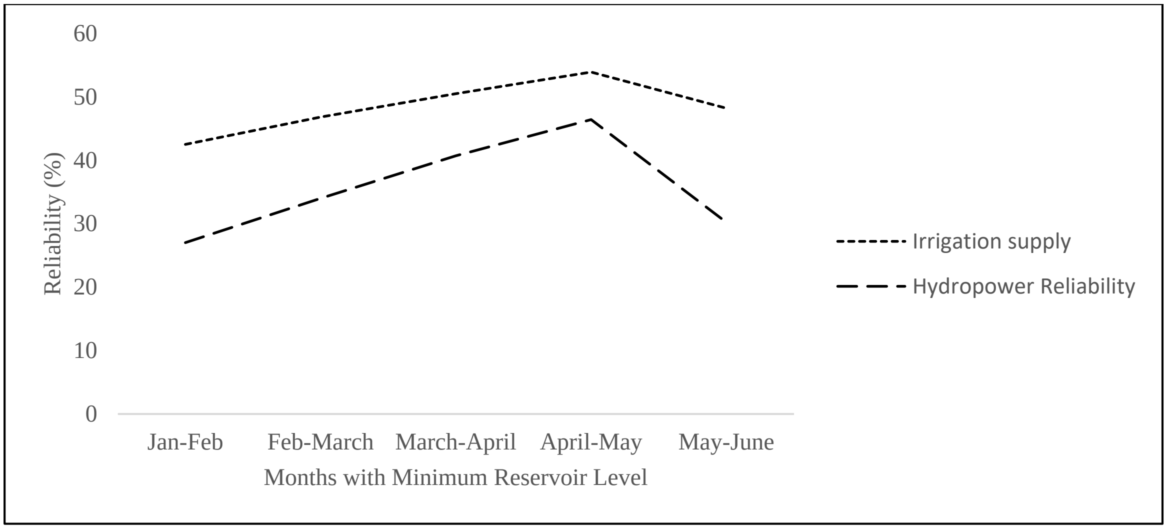

Figure 4.1 Reliability of Irrigation Supply, Hydropower Generation by Altering the Minimum Reservoir Level

meeting irrigation demands. Under the altered operations, water stored during the wet season, for irrigation in the dry season, elevates the water level in the reservoir. The releases from the reservoir are thus made according to the timings of hydropower and irrigation demands. In general, the reservoirs in other regions (East and West coast of USA, Russia, Canada, and China), which show positive hydropower and irrigation demand reliability, are operated under the same hydropower and irrigation demand timing. Figure 4.2 shows the altered reservoir operations (Rule Curve) selected for this study.

4.2 Effect of Maximum Hydraulic Outflow Changes on Flood Reliability

The improvement in flood control reliability required structural changes in the outflow capacity of the dam, as the altered operations could not substantially address flooding downstream of Tarbela. The analysis showed that the lowest outlet capacity resulted in the lowest of flood control reliability and vice versa. The flood control reliability

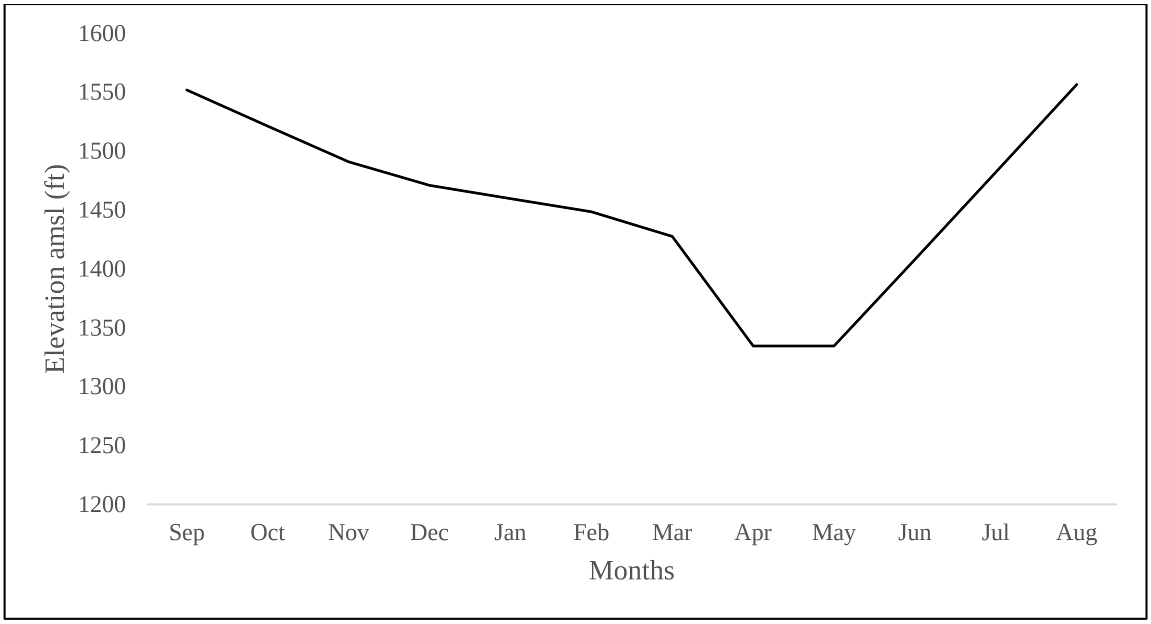

Figure 4.2 Proposed Rule Curve of Tarbela Dam

was maximum when the release capacity from the reservoir was 400,000 cfs (Figure 4.3), although the difference in the percentage flood control reliability is a fraction of a percent. However, even the fraction of the percent represents a flooding situation, whose adverse effects result in a loss of millions of dollars to the economy (Tariq and Van de Giesen 2012). In other words, the consequence of the small change in reliability is quite large – reinforcing the recommendation of this thesis to use multiple criteria that can capture the consequences better.

4.3 Percentage Improvement in RRVs with Proposed Operations for H-CR vs. H-PR Scenario and F-CR vs. F-PR Scenario

The improvement in the system performance with the proposed operations over current operations for historical and future climate and demand conditions was summarized

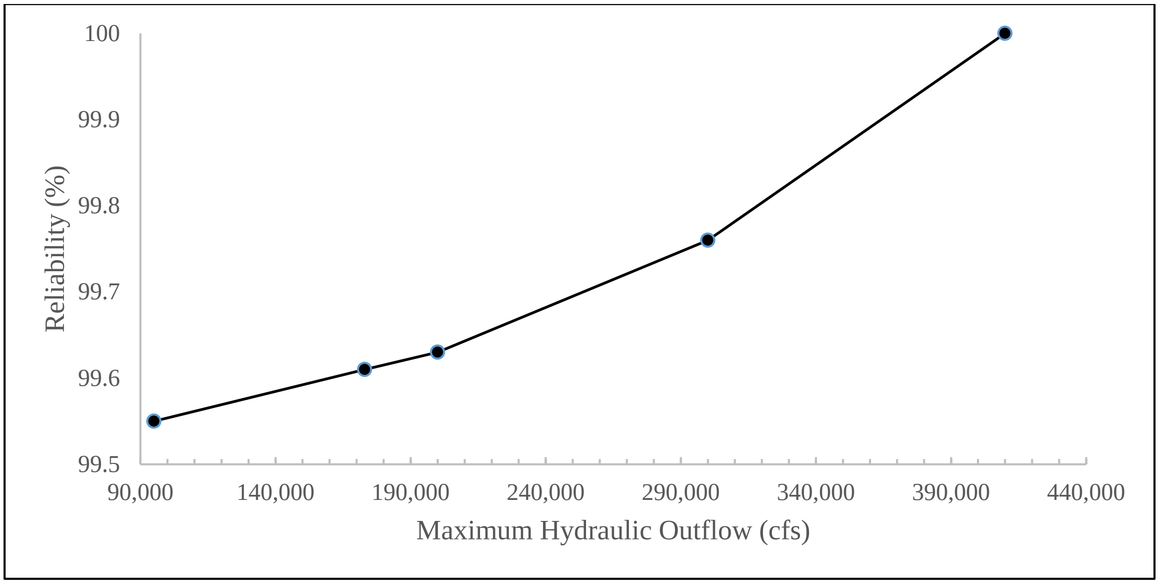

Figure 4.3 Percentage Change in Flood Control Reliability with Changes in Hydraulic Flow

as a 3 * 3 matrix with three objectives and three performance measures, which is shown in Tables 4.1 and 4.2.

The water supply and hydropower objectives had shown similar behavior with proposed operations under historical and future conditions. The reliability and resilience had improved for water supply and hydropower objective. However, the improvement in

Table 4.1: Percentage Increase in RRV with Proposed Operations for Historic Conditions

Objectives	Reliability	Resilience	Vulnerability
Water Supply	17 (SD)	67 (SD)	7 (NSD)
Hydropower Generation	34 (SD)	346 (SD)	22 (SD)
Flood Control	0.3 (SD)	-	-

Table 4.2: Percentage Increase in RRVs with Proposed Operations for Future Conditions

Objectives	Reliability	Resilience	Vulnerability
Water Supply	7 (NSD)	219 (SD)	11 (NSD)
Hydropower Generation	19 (SD)	136 (SD)	13 (NSD)
Flood Control	2 (SD)	-33 (SD)	-39 (SD)

reliability and resilience had made the system more vulnerable. The improvement in hydropower and irrigation water supply reliability and resilience resulted due to restricting all the releases from the outlet structures instead of spillways for historical conditions, and maximizing the releases from the outlet structures for the future climate and demand conditions. The releases from the outlet structure, because of installed turbines, increased the hydropower generation. In addition to this, high reservoir level during the wet season and shifting the minimum reservoir level in April-May increased the water availability for hydropower generation and meeting irrigation demand objectives for historical and future conditions. The increase in hydropower and irrigation water supply objective vulnerability is inferred to be linked with inherit system characteristics. In the light of previous studies, the systems with higher reliability and resilience usually result in higher vulnerability (Hashimoto et al. 1982, Moy et al. 1986, Kundzewicz and Kindler 1995).

The flood control reliability and vulnerability show an improvement, while resilience of the system to recover from the flood has decreased. For historical conditions, no flooding situation occurred with the increase in hydraulic outflow to 400,000 cfs. Therefore, improvement in the resilience and vulnerability could not be calculated. The decrease in flood control resilience for future conditions is also associated with the increase in the outlet capacity and higher water elevation during the wet season. The higher releases from the reservoir resulted in delaying of the system to return to a satisfactory state (release < 400,000 cfs).

The improvement with the proposed operations over current operations (as given in Tables 4.1 and 4.2) for all the objectives under two different climate and demand conditions were also statistically analyzed using a Two-Sample t-test at 95 % confidence interval at commonly chosen @-levels (maximum acceptable level of risk for rejecting a true null hypothesis) of 0.05. The improvement in the irrigation water supply, hydropower generation, and flood control objectives reliability and resilience also resulted in a significant difference with the proposed operations. The exceptions were the reliability of water supply and flood resilience under future conditions and hydropower generation vulnerability for historical conditions.

The results showed that the changes in the rule curve (reservoir operations) with the hydraulic outflow resulted in the improvement of performance measures of all the objectives. This outcome of the results was found to be consistent with the previous studies (Watts et al. 2011, Vonk 2013, Giuliani et al. 2016, Mateus and Tullos 2016).

4.4 Testing of Proposed Rule Curve on the Basis of Water Year for Historic Conditions

The performance of the proposed operations over the current operations on the basis of different types of water year showed that the gains in the objectives were sensitive to the inflows (Figure 4.4). This outcome is consistent with previous studies, which suggested that variation in the inflows generally impairs reservoir performance (Burn and Simonovic 1996, Mateus and Tullos 2016).

The hydropower generation and water supply objective showed a similar response to different type of water year. For instance, the percentage change in hydropower and irrigation water supply reliability with proposed operations over current operations showed substantial improvement during the historical low flow years followed by medium and high flow years (Figure 4.4). The low flow years are the most critical climate conditions in fulfilling these objectives, and an early filling of the reservoir (proposed operations) is aiding in achieving the objectives. This early filling of the reservoir is also one strategy suggested by previous studies (Mateus and Tullos 2016). The percentage change in hydropower generation and irrigation water supply resilience and vulnerability with proposed operations over current operations were slightly sensitive to the changes in the

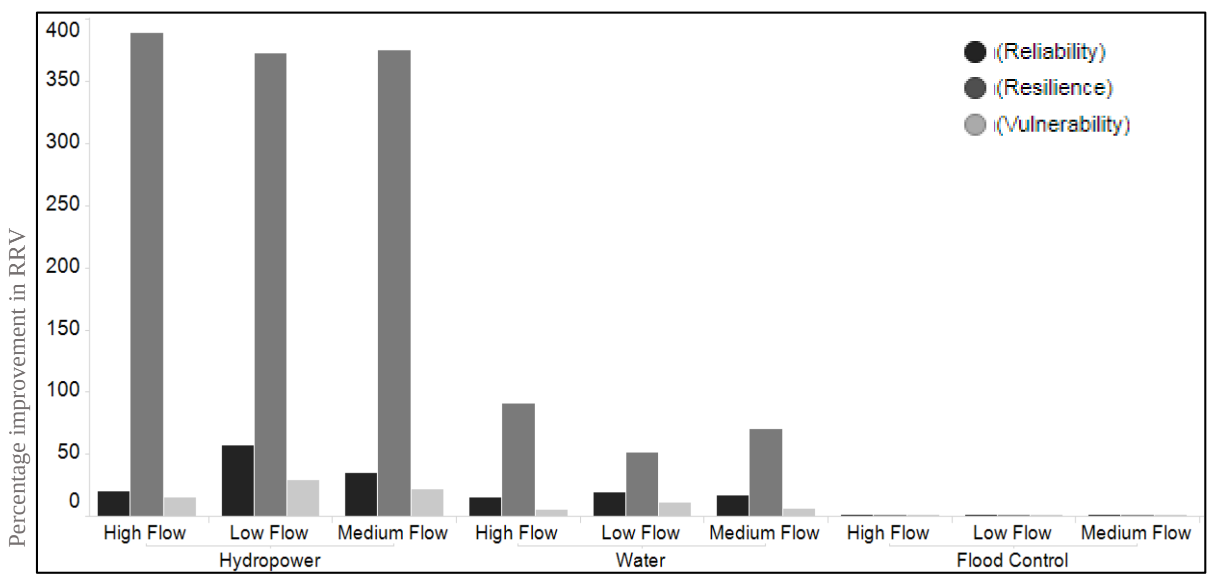

Figure 4.4 Percentage Improvement in the Objectives with Proposed Operations for Different Types of Water Year

inflows, with the resilience improving with the high flows and vulnerability increasing with low flows.

The flood control objective showed that the performance with the proposed operations is marginally high as compared to the current operations. For example, the percentage improvement in the reliability is maximum during the high flow years. It is because during the high flow years with current conditions, maximum water is released from the spillways. These uncontrolled releases from the reservoir are the main cause of flooding. With the proposed operations, all the release during the high flow years are controlled from the outlet structures, thus restricting the flow surpassing the 400,000 cfs flood threshold. The comparison of resilience and vulnerability could not be computed with the proposed operations as there was no failure (flooding condition) with the proposed operations.

The performance evaluation of the proposed operation on the basis of water years showed that the reliability of all the objectives is the most sensitive among the three chosen performance measures. The proposed operations resulted in the improvement of the performance measures under extreme climate conditions, which are low flows for hydropower generation and water supply and high flows for flood control. The vulnerability is the only performance measure that decreased with the climate conditions, not with the proposed operations.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In this study, the use of multiple objectives and multiple criteria (Reliability, Resilience, and Vulnerability) to evaluate and improve the performance of Tarbela Dam operations was investigated. The limitations of current operations of Tarbela Dam were explored, and new altered operations were recommended. The methodology of quantifying the improvement under proposed operations was based on computing the RRV of each objective (irrigation demand, hydropower generation, flood control) under the current operation strategy and the proposed altered operation strategy, for both historical and future climate and demand conditions. The RRV of respective operations and conditions combination were computed and explored to determine if improvements could be achieved.

The main conclusions that can be drawn from the research are as follows:

(1) Rule Curve Change Effects on Performance: The timing of the minimum target water elevation in Tarbela Reservoir was shifted 1 month earlier in the calendar year to April-May. The shifting of the minimum reservoir level established a better complement of hydropower generation and meeting irrigation water demands. Also, this proposed rule curve, with minimum level shifted to April-May, resulted in higher water storage during the high demand months (June – August) for hydropower generation and irrigation water supply.

(2) Maximum Hydraulic Outflow: The maximum hydraulic outflow played a pivotal role in controlling the flooding downstream of Tarbela. It was concluded that the maximum release capacity from the tunnels is needed to be increased to restrict the uncontrolled flows from the spillways. The downstream channel of Tarbela could take about 400,000 cfs safely without causing any significant damage; therefore, the releases from the tunnels are suggested to be increased to 400,000 cfs.

(3) Percentage Improvement in RRVs with Proposed Operations: The performance of the reservoir operations with proposed operations over current operations was evaluated for the entire period (historical and future) and the type of water year (high, medium, low average flow) for the historical record. The analysis for the entire period resulted in the exploration of gains in objectives with the proposed operations based on the historical and future climate and demand conditions. The performance evaluations of water supply for irrigation and hydropower objectives showed improvement in reliability and resilience with an increase in vulnerability. The flood control objective resulted in an increase in reliability and decrease in resilience and vulnerability. The analysis on the type of water year provided further insight into the improvement with proposed operations on the basis of low, medium and high average flow for the historical record. The proposed operations showed that significant improvement was made in the objectives for the critical climate combinations, which are low average flow for hydropower generation and water supply for irrigation and high average flow for flood control.

The limitations with the existing model are that the future climate and demand conditions were not forecasted. They were based on percentage increase and a decrease of the historical climate and inflow conditions. Although simplified, the approach does provide a reasonable stress test of the system that is useful for purposes of evaluating proposed changes. Given the uncertainty of projections and translation of those projections into a hydrologic response, the approach is reasonable.

The calibration of the model was based on the most uncertain parameter (evaporation), which was available in the data provided by the WAPDA. During the calibration procedure, the same value of evaporation was iterated and used for the entire calibration period. As the flow to Tarbela has high intra-annual variation, it is suggested in future work to use different evaporation values based on seasonal flows.

The improvement in the performance measures was only evaluated as the percentage increase or decrease of meeting objectives compared with current operations. This approach does not consider the tangible benefits such as cost/profit per unit release of water from the reservoir. This should be investigated as part of future work to confirm the conclusions drawn from determining the performance improvements.

Another uncertain factor not considered in this study was the change in live storage volume due to sedimentation and possible future upstream dam construction (especially Diamir Bhasha Dam). These factors could impact the storage volume required to meet the objectives, which could affect the system performance in terms of RRV. Additional alterations in operations may be needed.

Finally, the approach of using simulation to investigate selected operations alterations could be refined to include optimization. The investigation was thorough; therefore, optimization is not expected to significantly alter the results. However, as the solution space and constraints are made more complicated, optimization may be needed.

APPENDIX A

DATA REQUIRED FOR WEAP MODEL

Table A.1 Input Data to Represent the Tarbela Reservoir in WEAP

Parameter		Value	Significance of Parameter	Quality
Physical	Storage Capacity	7.7 MAF	Maximum Volume available for water allocation to meet the objectives	Verified
	Initial Storage Capacity	3.1 MAF	The initial storage in the reservoir before the start of the operation in June 1976.	Uncertain
	Volume-Elevation Curve	96 points	This curve is used to calculate the volume of the reservoir for a particular elevation and vice versa.	Verified

Table A.1 Continued

Parameter		Value	Significance of Parameter	Quality
	Maximum Hydraulic Outflow	173,000 cfs	The maximum release possible from the tunnels installed in the dam body.	Verified
	Evaporation Data	Daily Data from July 1976-December 1997 and March 2003-December 2013	Losses due to evaporation reduce the water level in the reservoir, thus affecting the available water to allocate for the objectives.	Uncertain
Operation	Top of Conservation	Rule Curve of Tarbela	This refers to the maximum desired level intended to be maintained in the reservoir.	Verified
	Top of inactive	583,000 AF	The amount of water not available for the allocation	Uncertain

Table A.1 Continued

Parameter		Value	Significance of Parameter	Quality
	Top of Buffer	583,000 AF	It is assumed as the top of inactive for this research study	Uncertain
	Maximum Turbine Outflow	173,000 cfs	Maximum amount of water flowing through the turbines installed with the hydropower generation	Verified
Hydropower	Tail Water Elevation	1,200 ft amsl	Elevation level where the turbines are installed in the Tarbela reservoir.	Acceptable
	Plant Factor	100 %	Percentage of each day that hydropower plant is running	Uncertain
	Generating Efficiency	75 %	Electricity generated by hydropower input	Uncertain
Cost	Fixed Benefits	$ 3 per AF of release and 30 cents per KWH energy production	Benefits calculated from the Tarbela reservoir from the releases.	Acceptable

Table A.1 Continued

Parameter		Value	Significance of Parameter	Quality
Priority	As per basis of the operation	1^{st}, 2^{nd}, and 3^{rd} priority is given to the reservoir, irrigation water supply and hydropower generation	Tarbela reservoir having the first priority means that the top of conservation/Rule curve will be followed by the Model. After achieving the desired level, filling or drawdown of the reservoir will be restricted, and all excess water will be released to meet the irrigation supply and then the hydropower requirement.	Verified

APPENDIX B

WEAP MODEL RESULTS

Table B.1 Reliability, Resilience, and Vulnerability for Historical Conditions

	Reliability			
Objectives	Current Operations		Proposed Operations	
	Mean	Std. Deviation	Mean	Std. Deviation
Water Supply	45%	5.73	52%	5.46
Hydropower Generation	37%	7.74	50%	2.52
Flood Control	99.71%	0.42	100%	-

	Resilience			
Objectives	Current Operations		Proposed Operations	
	Mean	Std. Deviation	Mean	Std. Deviation
Water Supply	14%	4.12	24%	4.68
Hydropower Generation	3%	1.12	12%	0.30
Flood Control	-	-	-	-

Table B.1 Continued

Objectives	Vulnerability			
	Current Operations		Proposed Operations	
	Mean	Std. Deviation	Mean	Std. Deviation
Water Supply	23,423 cfs	3,474	25,022 cfs	5,124
Hydropower Generation	291 MW	116	355 MW	120
Flood Control	-	-	-	-

Table B.2 Reliability, Resilience, and Vulnerability for Future Conditions

Objectives	Reliability			
	Current Operations		Proposed Operations	
	Mean	Std. Deviation	Mean	Std. Deviation
Water Supply	50%	36.65	53%	35.84
Hydropower Generation	37%	14.56	44%	14.30
Flood Control	97.34%	3.77	99.18%	1.52

Table B.2 Continued

	Resilience			
Objectives	Current Operations		Proposed Operations	
	Mean	Std. Deviation	Mean	Std. Deviation
Water Supply	6%	4.97	21%	14.80
Hydropower Generation	2%	0.48	4%	1.13
Flood Control	7%	8.82	5%	5.50

	Vulnerability			
Objectives	Current Operations		Proposed Operations	
	Mean	Std. Deviation	Mean	Std. Deviation
Water Supply	55,495 cfs	62,591	61,833 cfs	67,609
Hydropower Generation	340 MW	484	392 MW	537
Flood Control	10,591 cfs	18,569	6,419 cfs	12,603

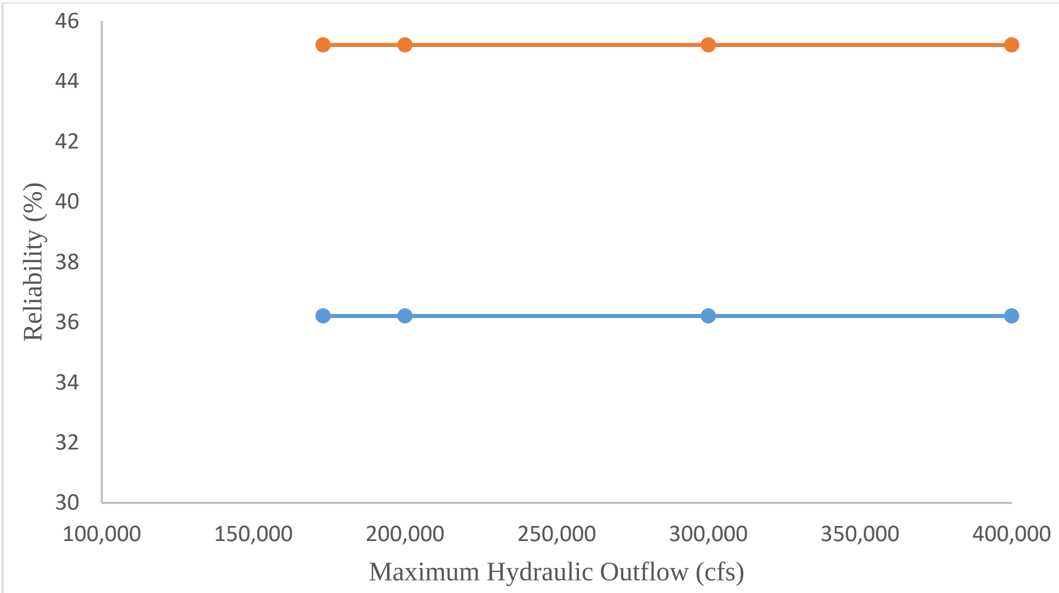

Figure B.1 Effect of Hydraulic Outflow on Reliability of Water Supply for Irrigation and Hydropower

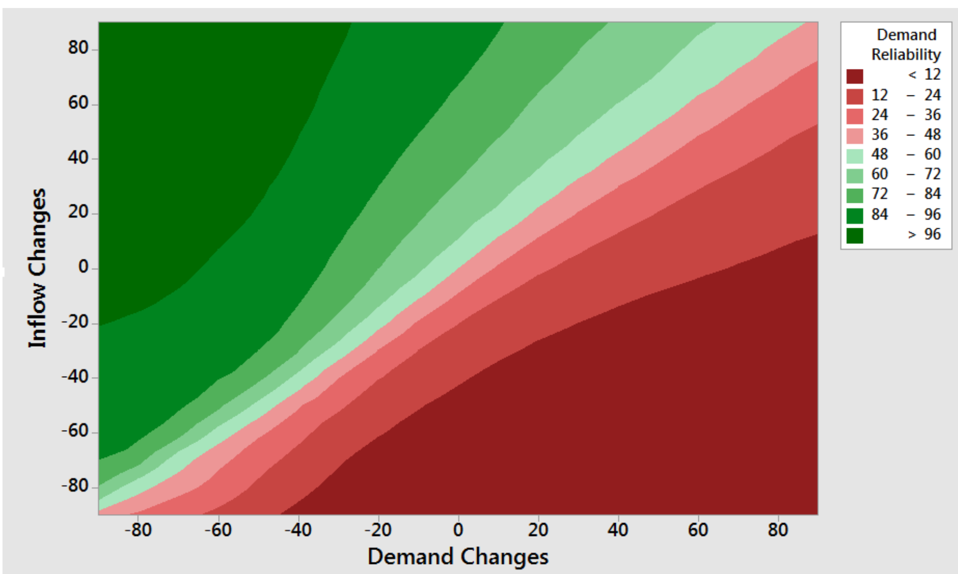

Figure B.2 Contour Plot of Sensitivity of Demand Reliability to the Inflow and Demand Changes

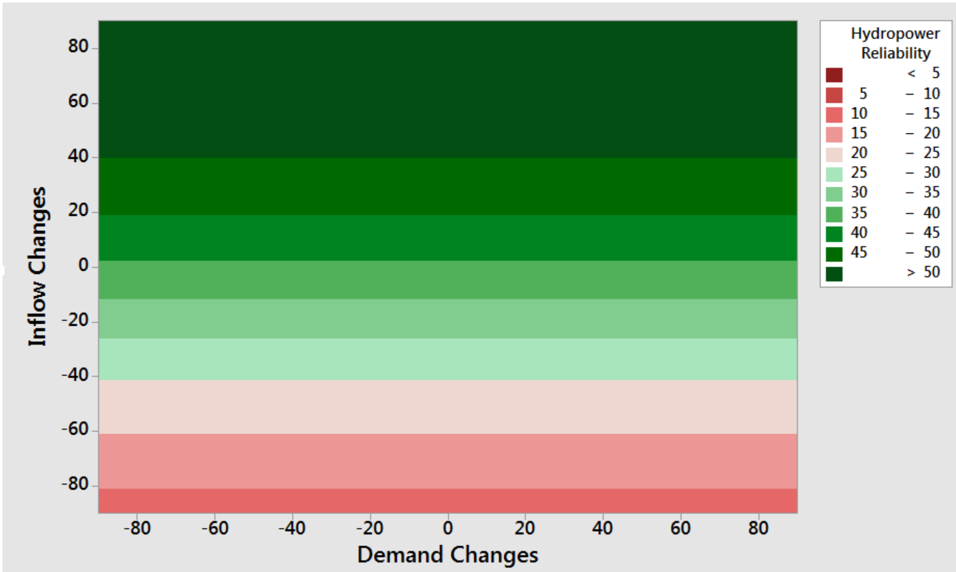

Figure B.3 Contour Plot of Sensitivity of Hydropower Reliability to the Inflow and Demand Changes

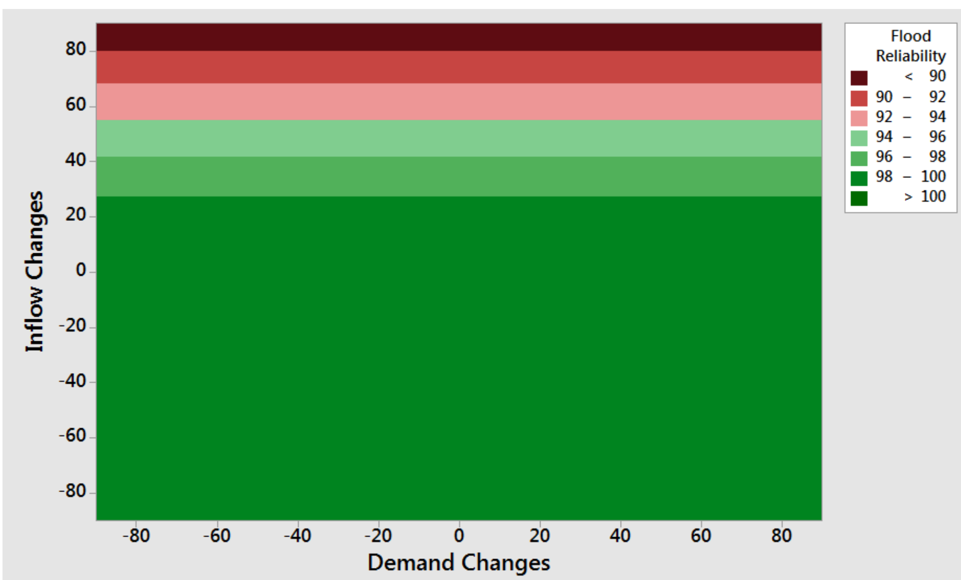

Figure B.4 Contour Plot of Sensitivity of Flood Control Reliability to the Inflow and Demand Changes

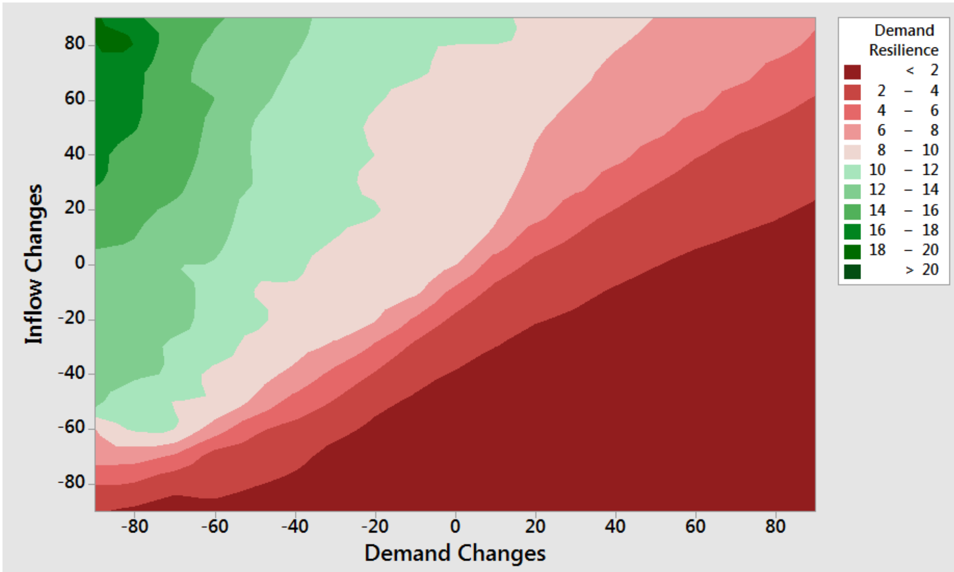

Figure B.5 Contour Plot of the Sensitivity of Water Demand Resilience to the Inflow and Demand Changes

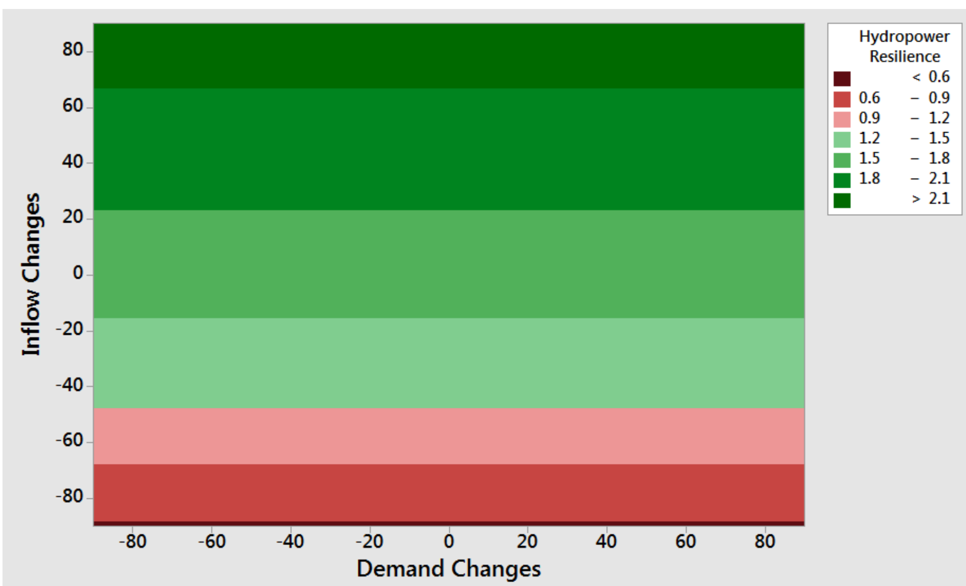

Figure B.6 Contour Plot of Sensitivity of Hydropower Resilience to the Inflow and Demand Changes

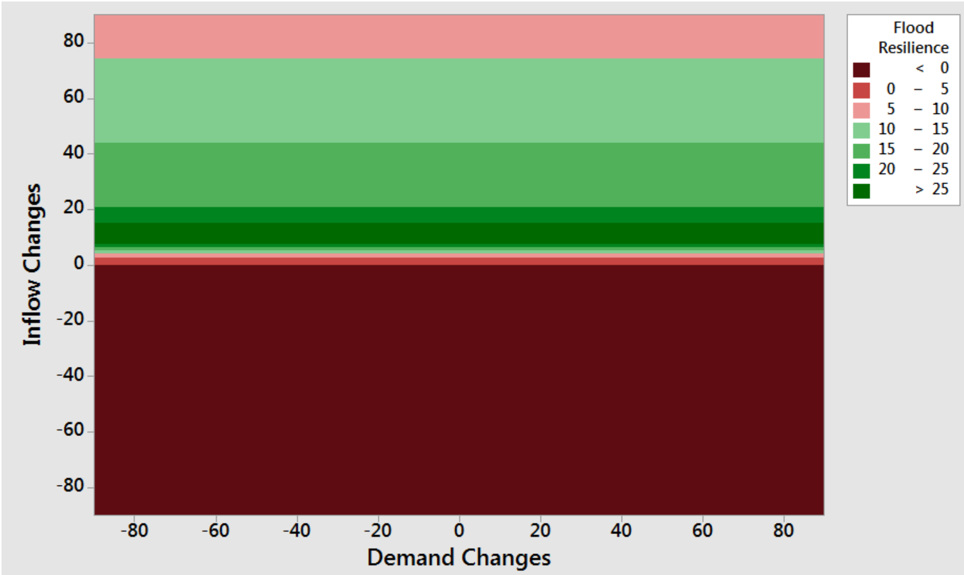

Figure B.7 Contour Plot of Sensitivity of Flood Control Resilience to the Inflow and Demand Changes

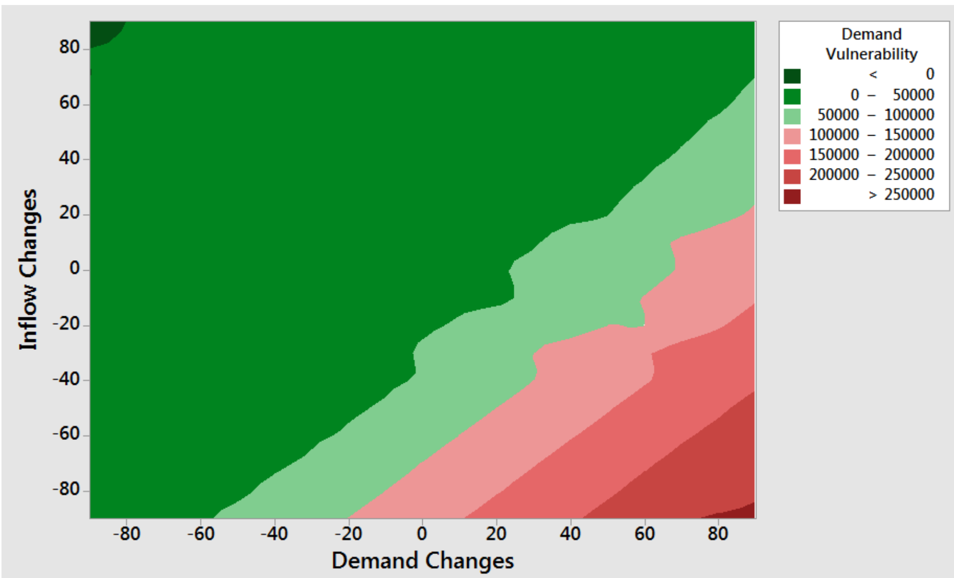

Figure B.8 Contour Plot of Sensitivity of Demand Vulnerability to the Inflow and Demand Changes

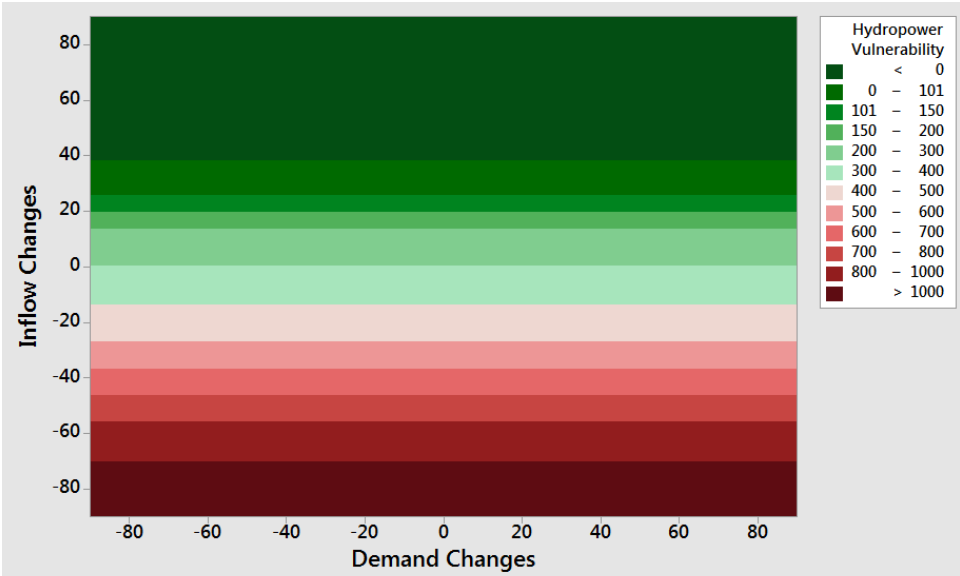

Figure B.9 Contour Plot of Sensitivity of Hydropower Vulnerability to the Inflow and Demand Changes

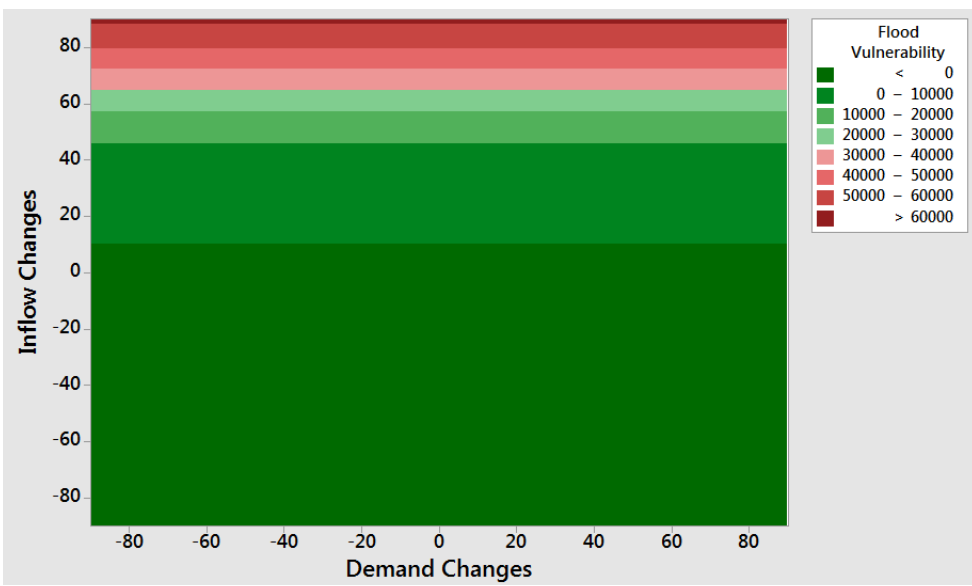

Figure B.10 Contour Plot of Sensitivity of Flood Control Vulnerability to the Inflow and Demand Changes

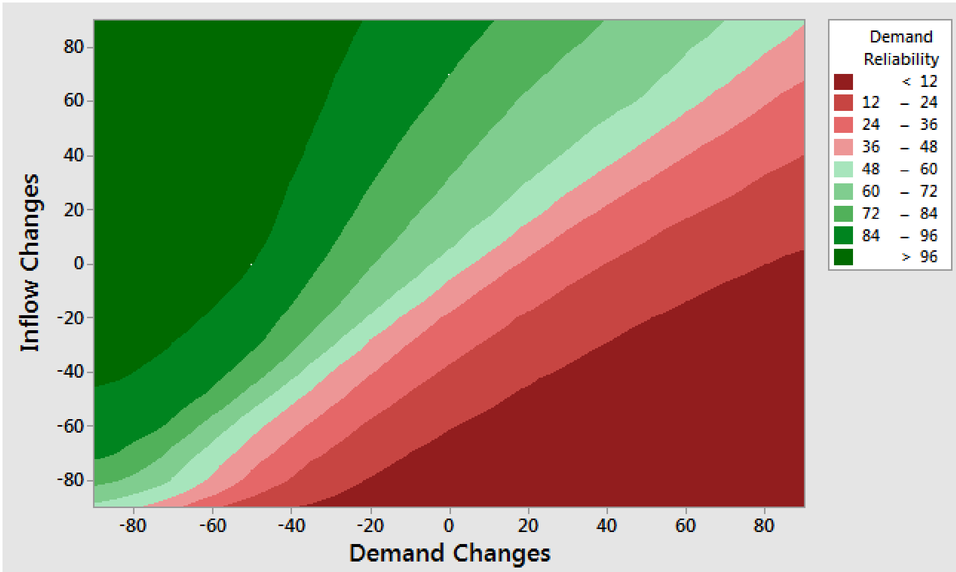

Figure B.11 Contour Plot of Sensitivity of Demand Reliability to the Inflow and Demand Changes

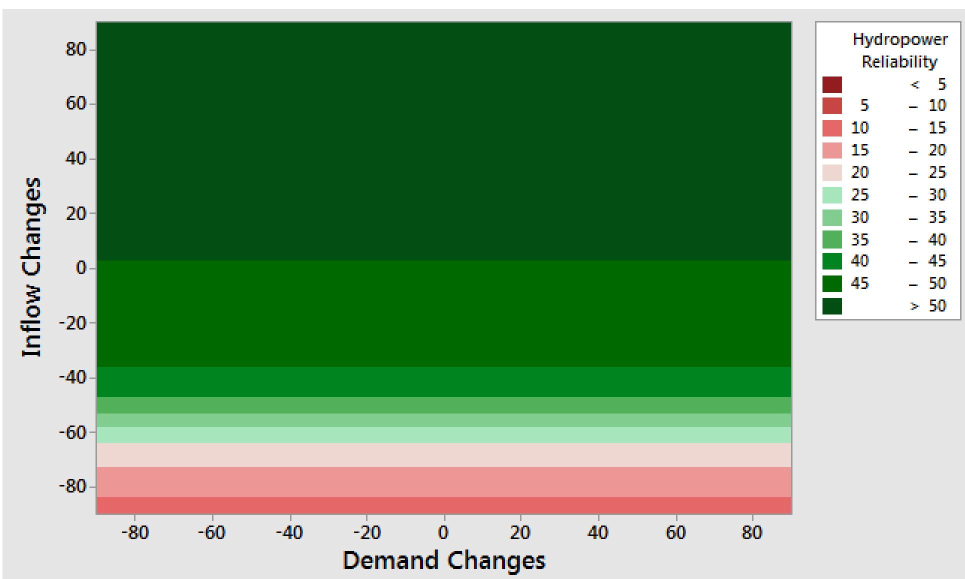

Figure B.12 Contour Plot of Sensitivity of Hydropower Reliability to the Inflow and Demand Changes

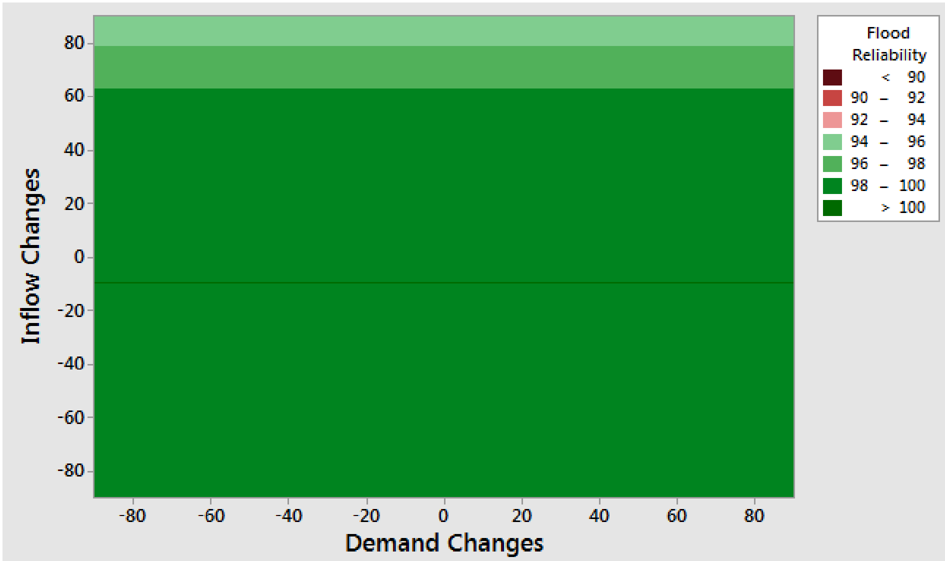

Figure B.13 Contour Plot of Sensitivity of Flood Control Reliability to the Inflow and Demand Changes

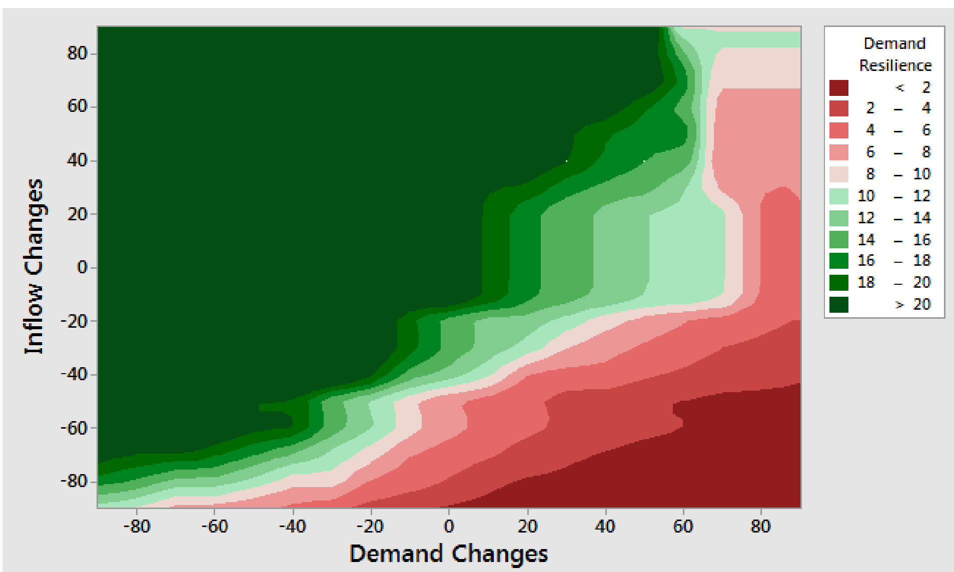

Figure B.14 Contour Plot of the Sensitivity of Water Demand Resilience to the Inflow and Demand Changes

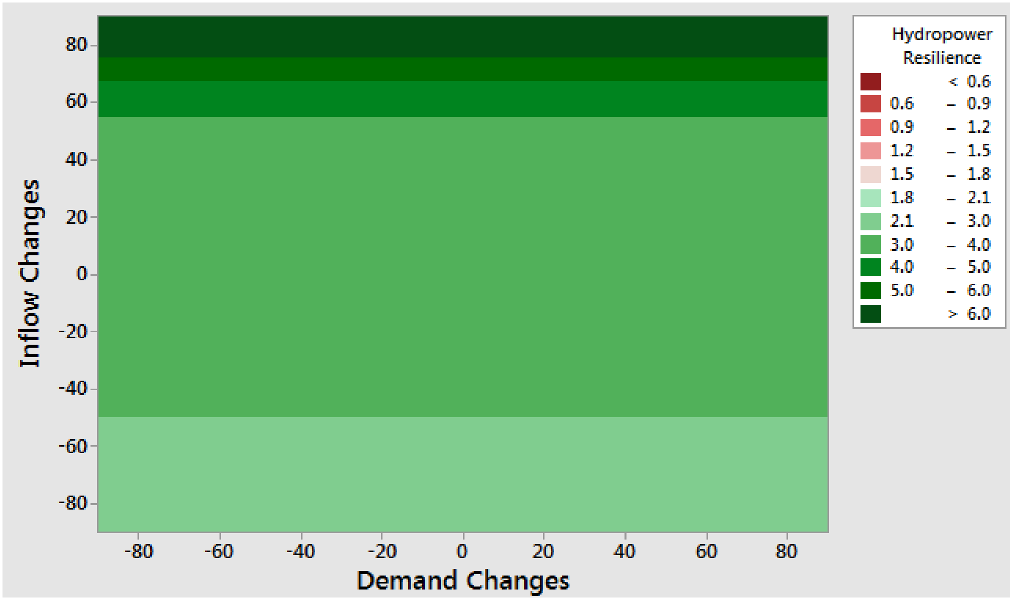

Figure B.15 Contour Plot of the Sensitivity of Hydropower Resilience to the Inflow and Demand Changes

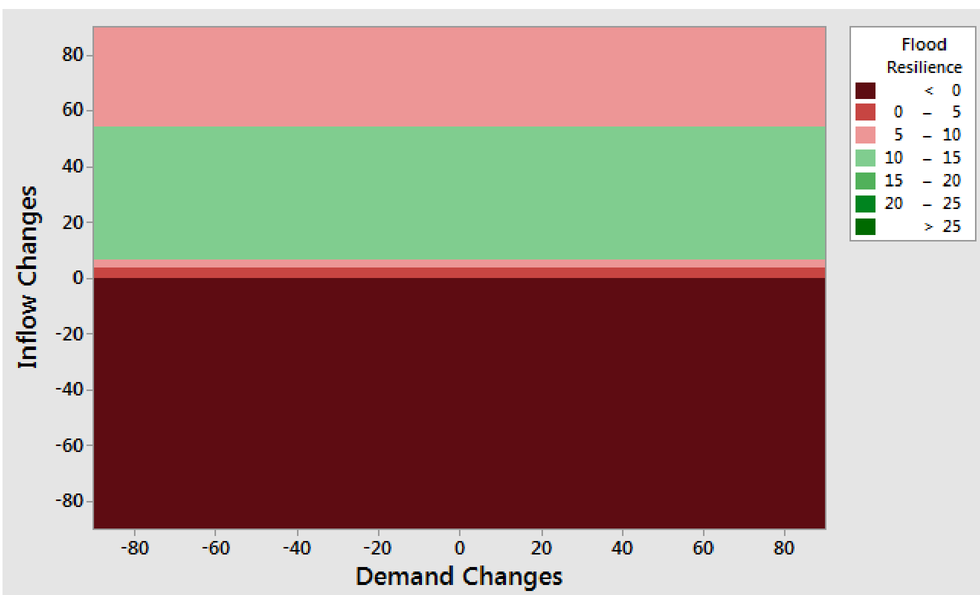

Figure B.16 Contour Plot of Sensitivity of Flood Control Resilience to the Inflow and Demand Changes

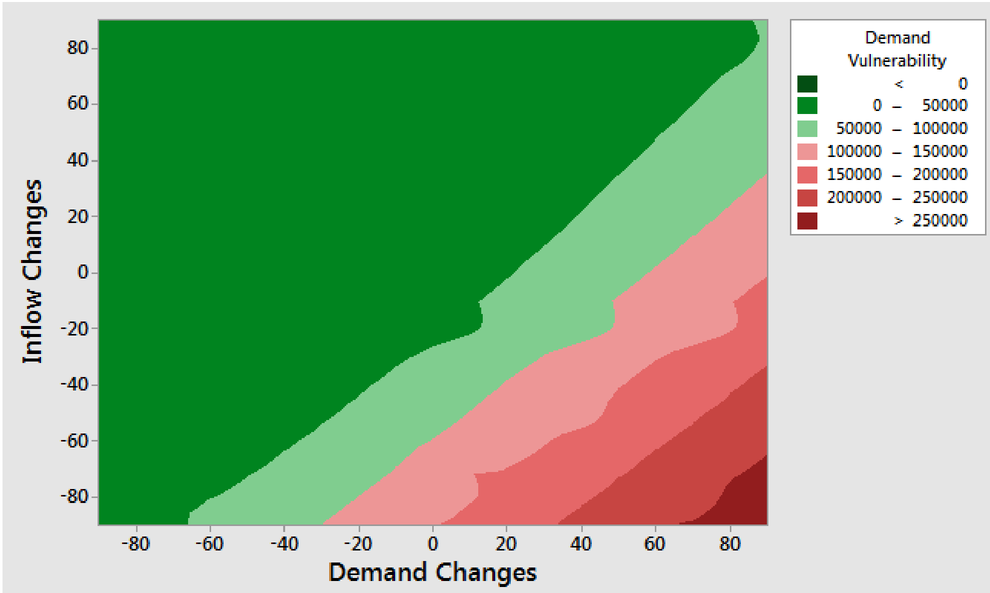

Figure B.17 Contour Plot of Sensitivity of Demand Vulnerability to the Inflow and Demand Changes

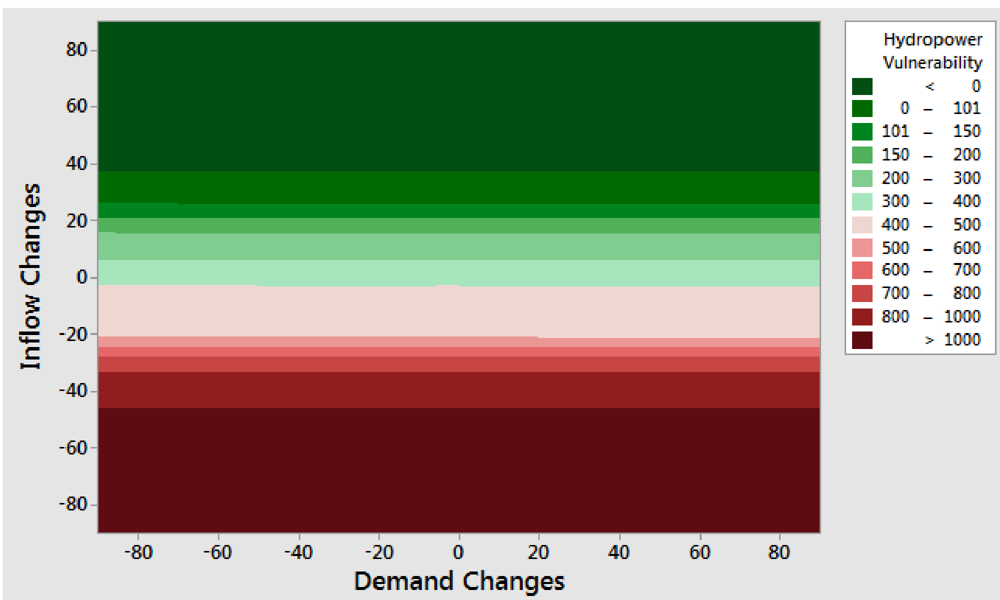

Figure B.18 Contour Plot of Sensitivity of Hydropower Vulnerability to the Inflow and Demand Changes

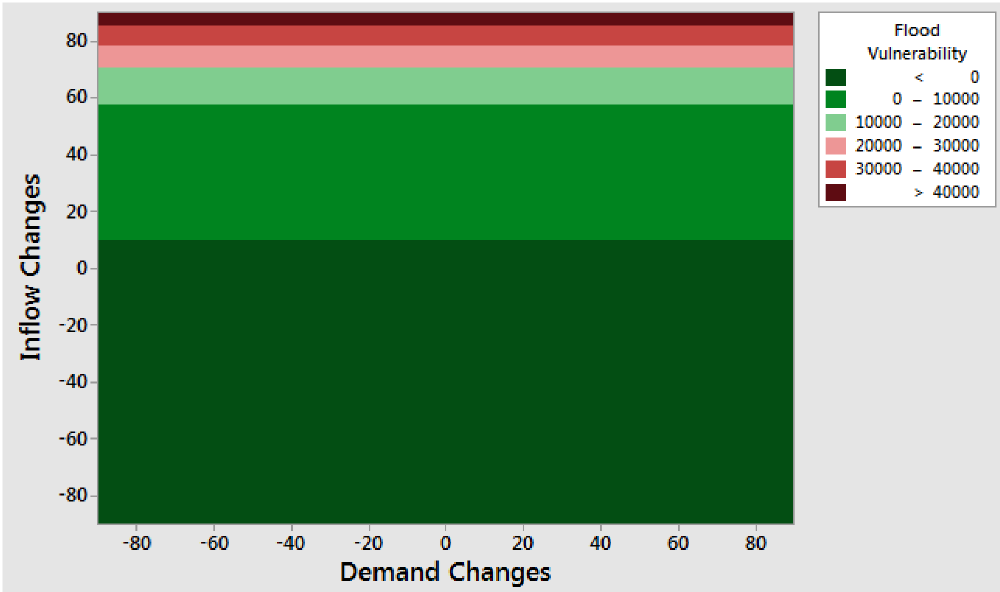

Figure B.19 Contour Plot of Sensitivity of Flood Control Vulnerability to the Inflow and Demand Changes

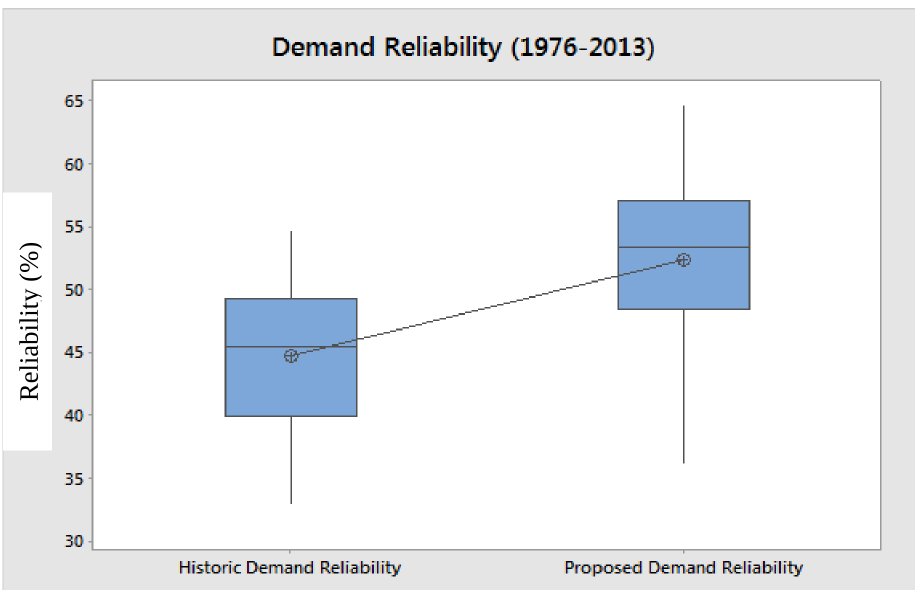

Figure B.20 Box Plot of Demand Reliability from 1976-2013 for Historical and Proposed Operations

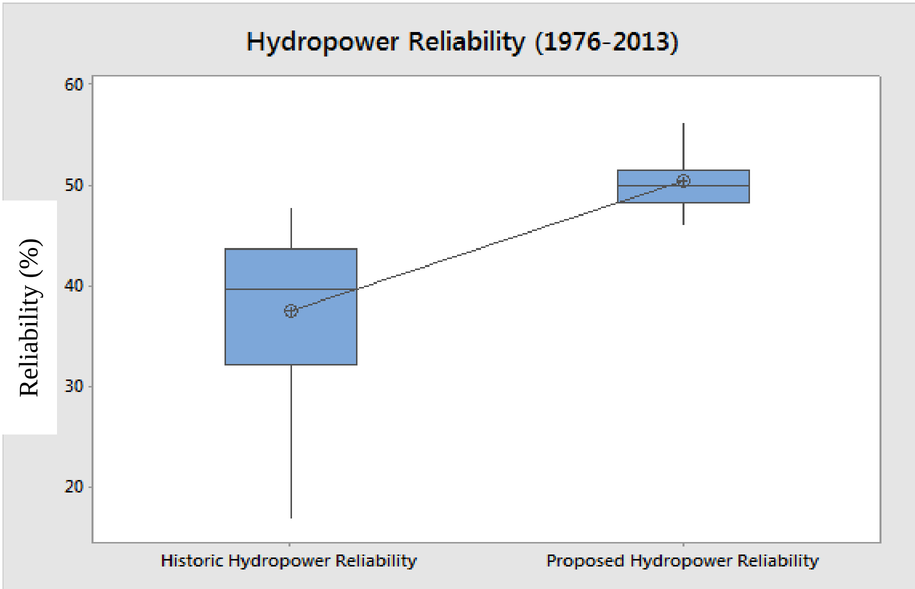

Figure B.21 Box Plot of Hydropower Generation Reliability from 1976-2013 for Historical and Proposed Operations

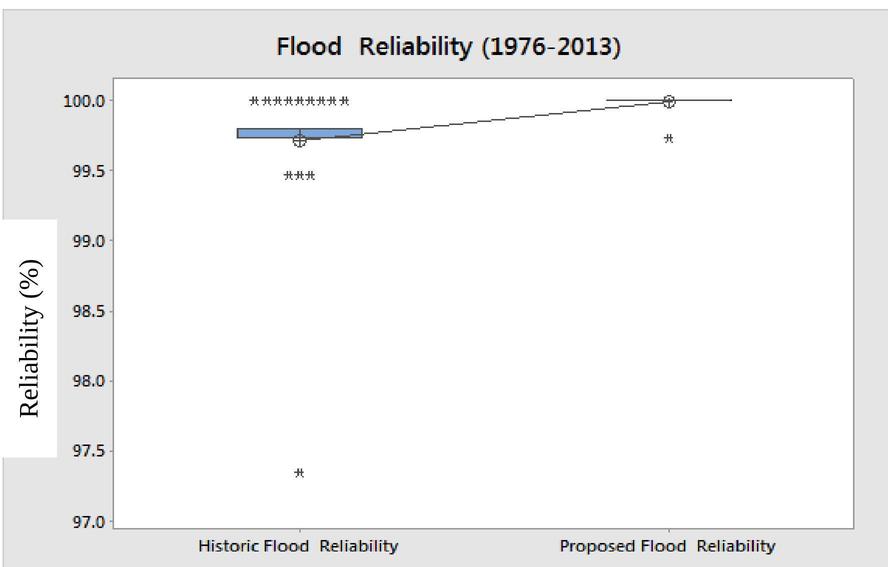

Figure B.22 Box Plot of Flood Control Reliability from 1976-2013 for Historical and Proposed Operations

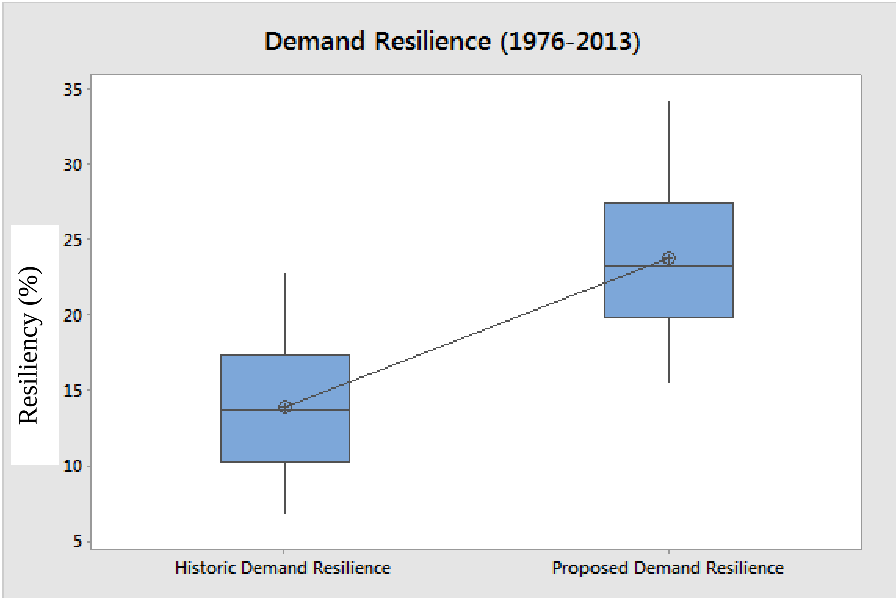

Figure B.23 Box Plot of Demand Resilience from 1976-2013 for Historical and Proposed Operations

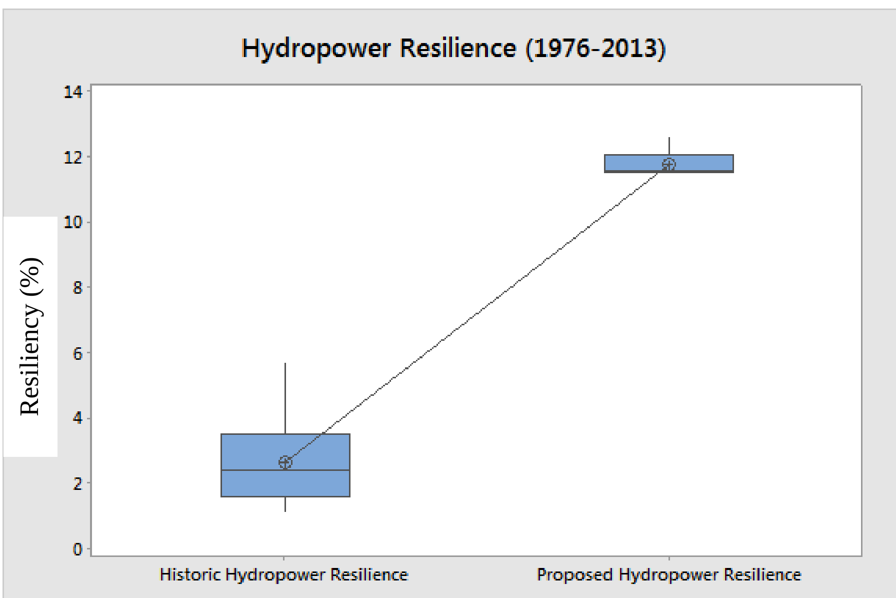

Figure B.24 Box Plot of Hydropower Resilience from 1976-2013 for Historical and Proposed Operations

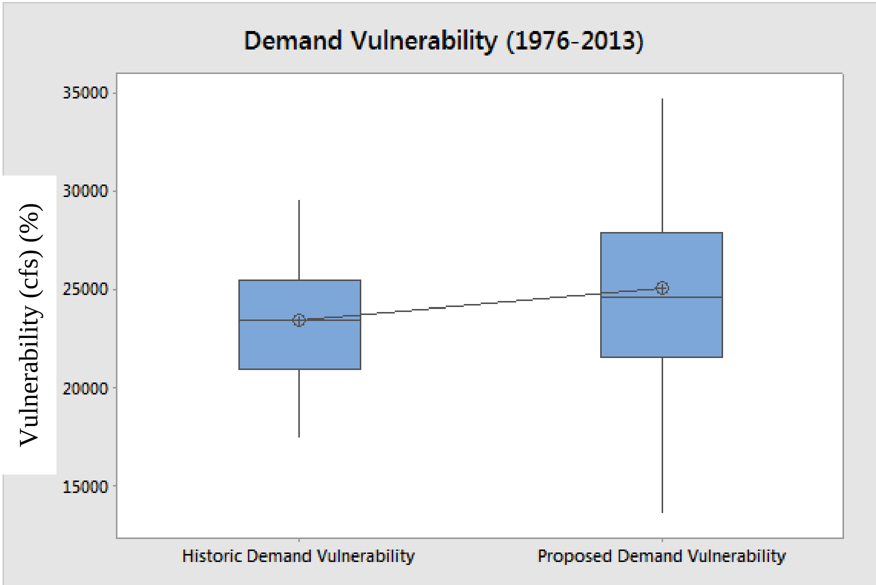

Figure B.25 Box Plot of Demand Vulnerability from 1976-2013 for Historical and Proposed Operations

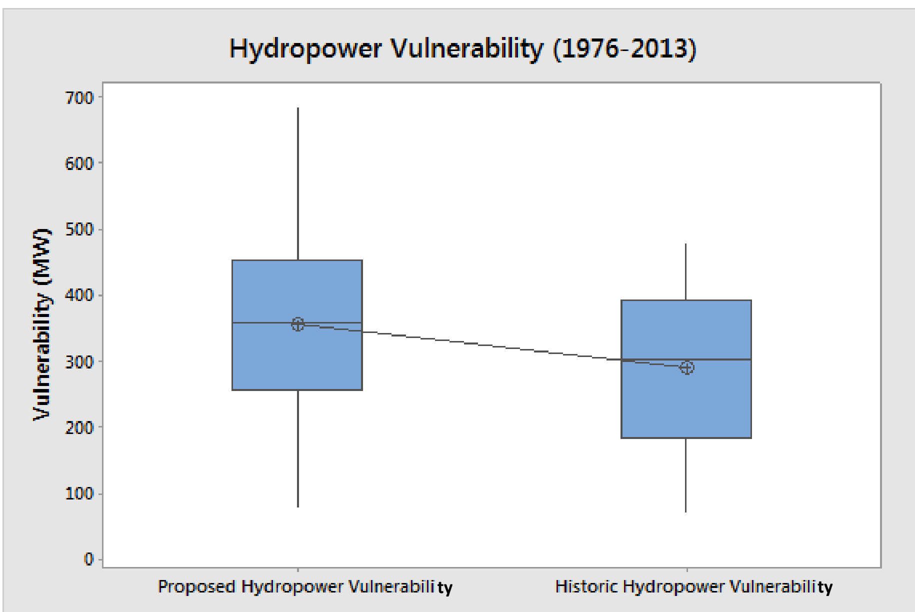

Figure B.26 Box Plot of Hydropower Vulnerability from 1976-2013 for Historical and Proposed Operations

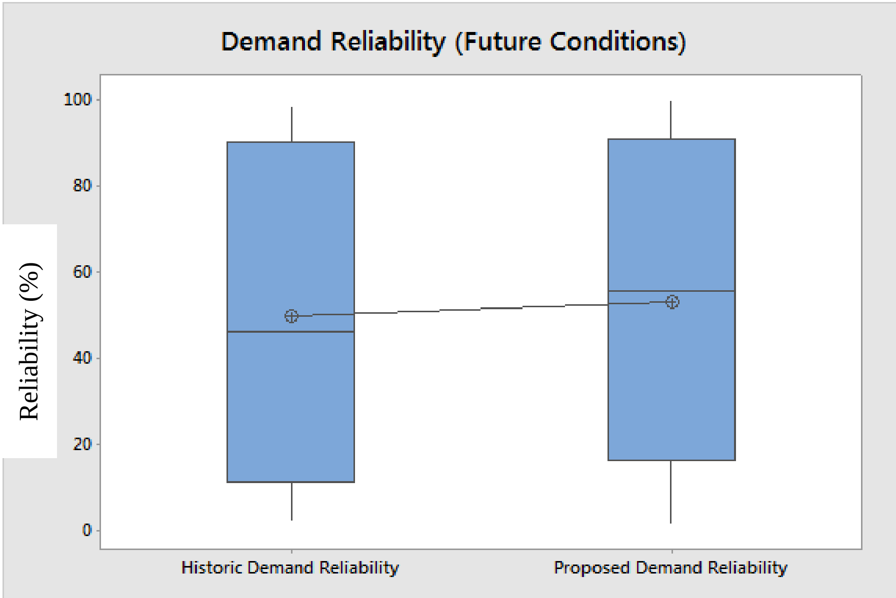

Figure B.27 Box Plot of Demand Reliability for Historical and Proposed Operations with Future Conditions

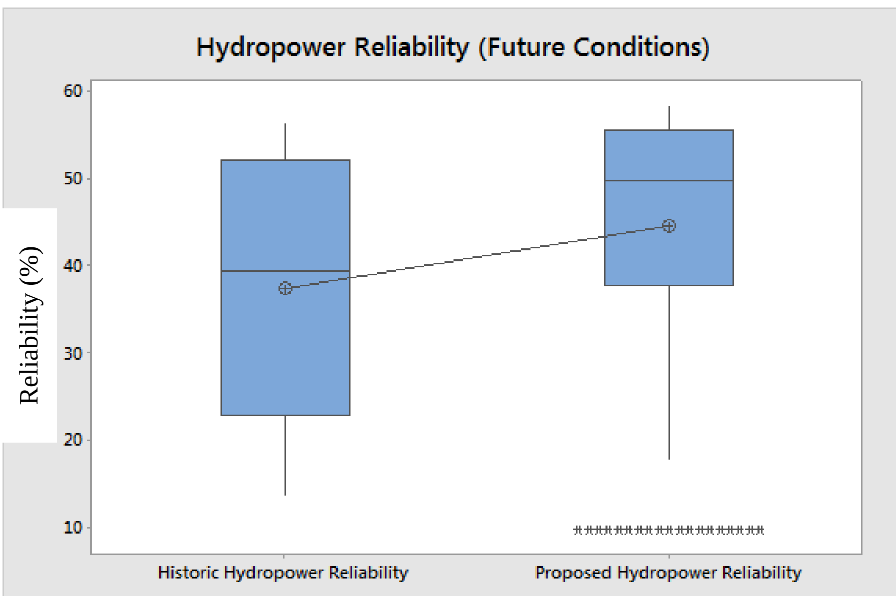

Figure B.28 Box Plot of Hydropower Reliability for Historical and Proposed Operations with Future Conditions

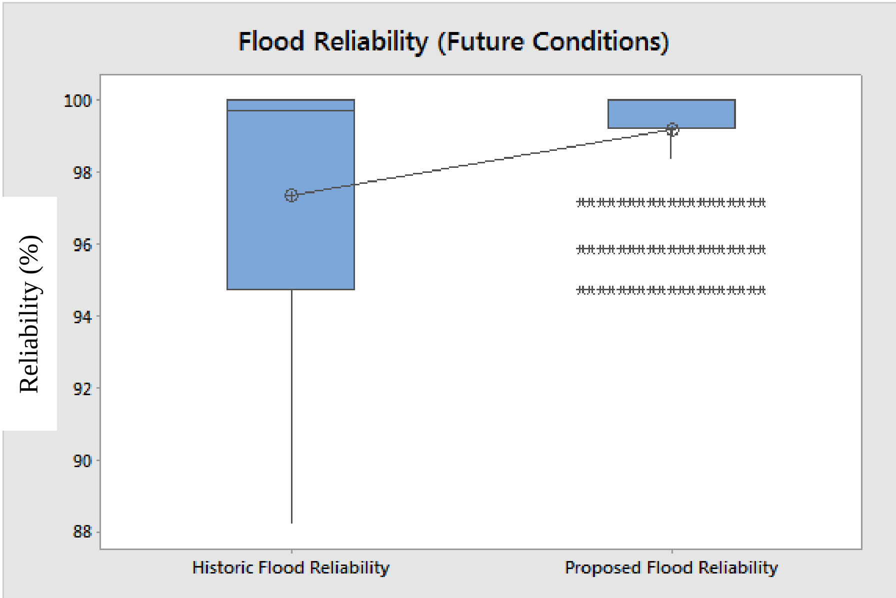

Figure B.29 Box Plot of Flood Control Reliability for Historical and Proposed Operations with Future Conditions

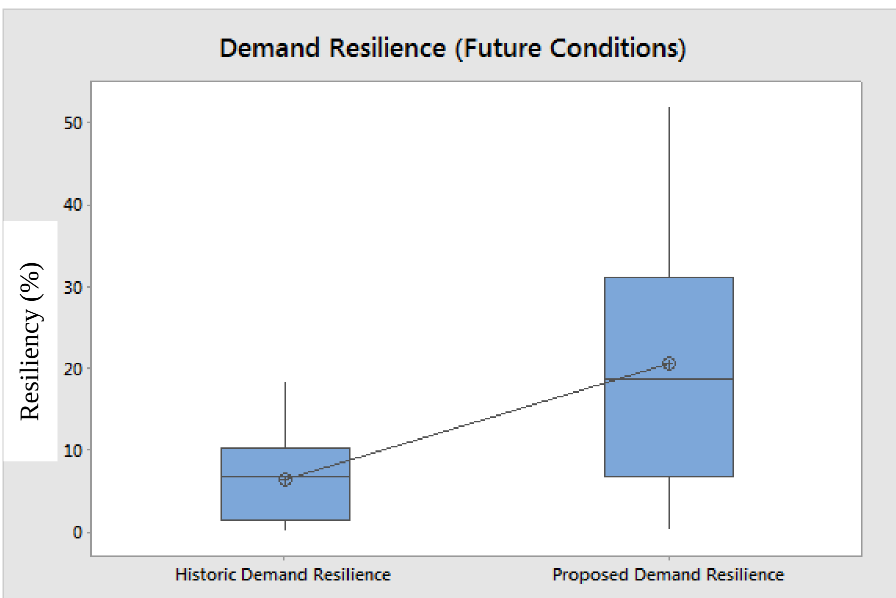

Figure B.30 Box Plot of Demand Resilience for Historical and Proposed Operations with Future Conditions

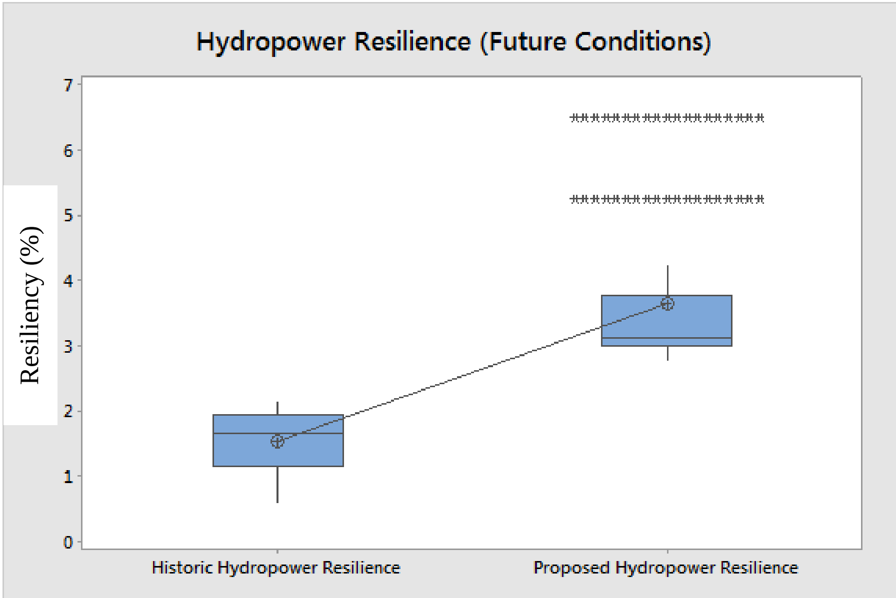

Figure B.31 Box Plot of Hydropower Resilience for Historical and Proposed Operations with Future Conditions

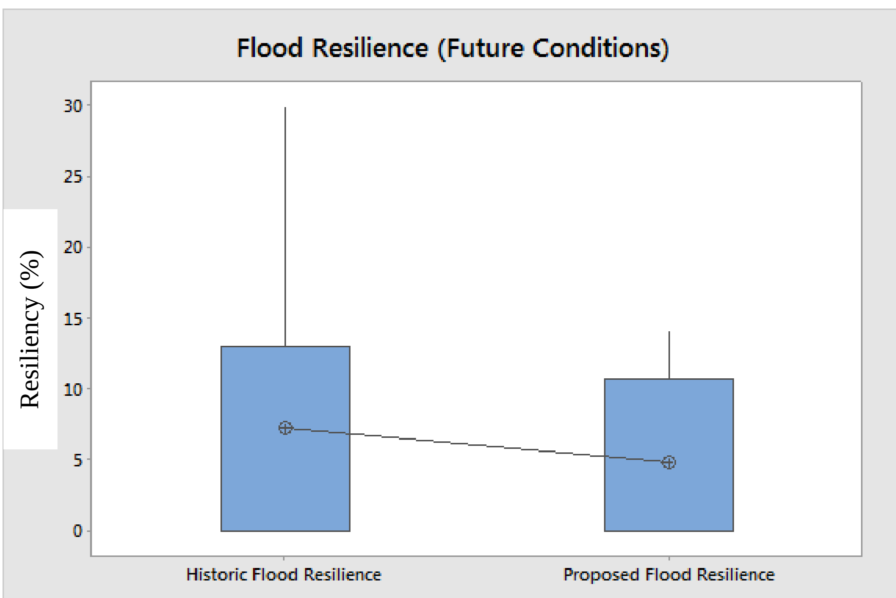

Figure B.32 Box Plot of Flood Control Resilience for Historical and Proposed Operations with Future Conditions

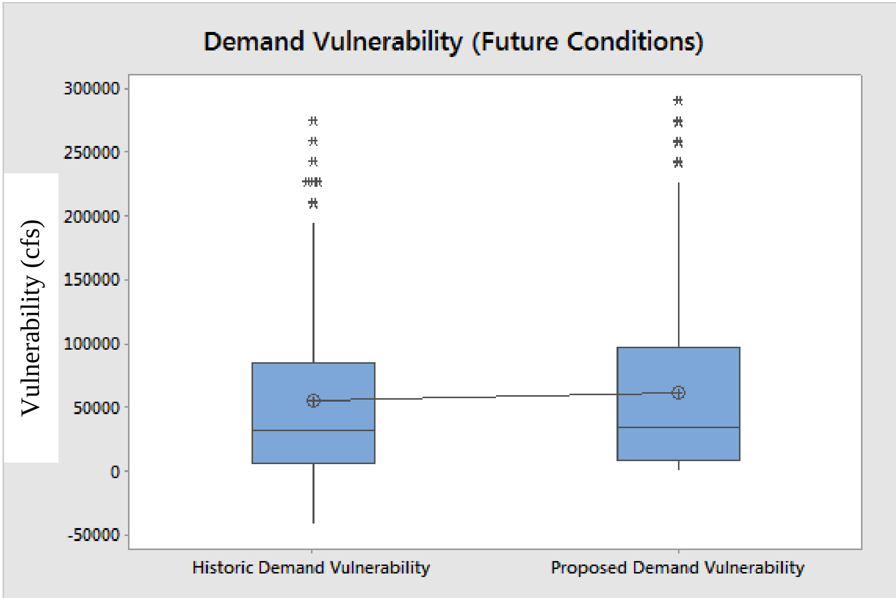

Figure B.33 Box Plot of Demand Vulnerability for Historical and Proposed Operations with Future Conditions

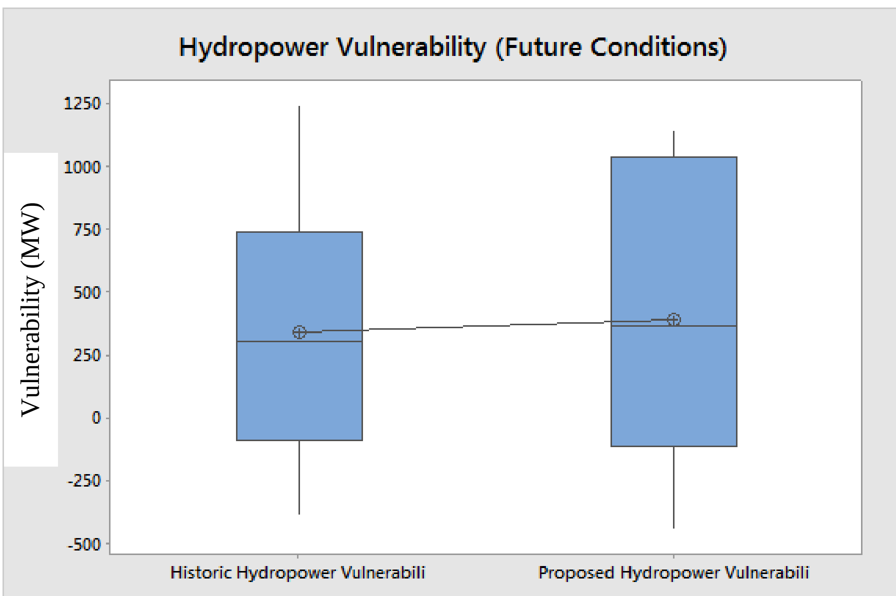

Figure B.34 Box Plot of Hydropower Vulnerability for Historical and Proposed Operations with Future Conditions

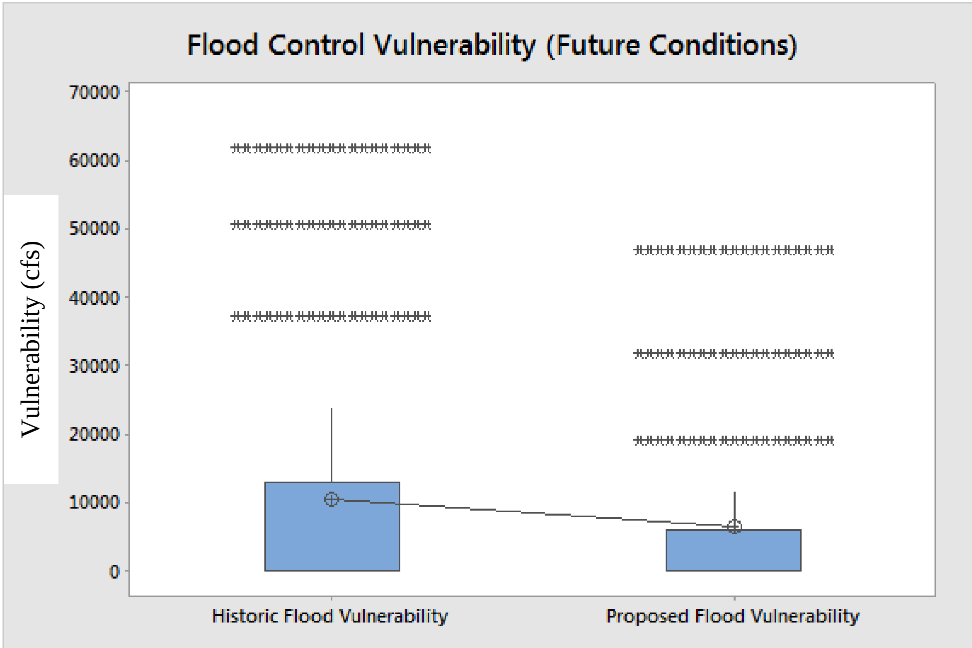

Figure B.35 Box Plot of Flood Control Vulnerability for Historical and Proposed Operations with Future Conditions

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